Prepared in cooperation with the U.S. Department of Agriculture-Forest Service

Geochemistry of Mine Waste and Mill Tailings, Meadow Deposits, Streambed Sediment, and General Hydrology and Water Quality for the Frohner Meadows Area, Upper Lump Gulch, Jefferson County, Montana

By Terry L. Klein, Michael R. Cannon, and David L. Fey

Open-File Report 2004-1254

U.S. Department of the Interior
U.S. Geological Survey

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CONVERSION FACTORS, DATUM, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.028317	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer

Abbreviated units used in this report:

µL	microliter
µg/L	micrograms per liter
µm	micrometer (micron)
µS/cm	microsiemens per centimeter at 25 degrees Celsius
meq/L	milliequivalents per liter
mg/L	milligrams per liter
mm	millimeter
m	meter
ft	foot
nm	nanometer
M	molar

Some acronyms used in this report:

HCl	hydrochloric acid
HNO_3	nitric acid
$HClO_4$	perchloric acid
HF	hydrofluoric acid
H_2O_2	hydrogen peroxide

GEOCHEMISTRY OF MINE WASTE AND MILL TAILINGS, MEADOW DEPOSITS, STREAMBED SEDIMENT, AND GENERAL HYDROLOGY AND WATER QUALITY FOR THE FROHNER MEADOWS AREA, UPPER LUMP GULCH, JEFFERSON COUNTY, MONTANA

ABSTRACT

Frohner Meadows, an area of low-topographic gradient subalpine ponds and wetlands in glaciated terrane near the headwaters of Lump Gulch (a tributary of Prickly Pear Creek), is located about 15 miles west of the town of Clancy, Montana, in the Helena National Forest. Mining and ore treatment of lead-zinc-silver veins in granitic rocks of the Boulder batholith over the last 120 years from two sites (Frohner mine and the Nellie Grant mine) has resulted in accumulations of mine waste and mill tailings that have been distributed downslope and downstream by anthropogenic and natural processes.

This report presents the results of an investigation of the geochemistry of the wetlands, streams, and unconsolidated-sediment deposits and the hydrology, hydrogeology, and water quality of the area affected by these sources of ore-related metals. Ground water sampled from most shallow wells in the meadow system contained high concentrations of arsenic, exceeding the Montana numeric water-quality standard for human health. Transport of cadmium and zinc in ground water is indicated at one site near Nellie Grant Creek based on water-quality data from one well near the creek. Mill tailings deposited in upper Frohner Meadow contribute large arsenic loads to Frohner Meadows Creek; Nellie Grant Creek contributes large arsenic, cadmium, and zinc loads to upper Frohner Meadows. Concentrations of total-recoverable cadmium, copper, lead, and zinc in most surface-water sites downstream from the Nellie Grant mine area exceeded Montana aquatic-life standards. Nearly all samples of surface water and ground water had neutral to slightly alkaline pH values.

Concentrations of arsenic, cadmium, lead, and zinc in streambed sediment in the entire meadow below the mine waste and mill tailings accumulations are highly enriched relative to regional watershed-background concentrations and exceed consensus-based, probable-effects concentrations for streambed sediment at most sites. Cadmium, copper, and zinc typically are adsorbed to the surface coatings of streambed-sediment grains. Mine waste and mill tailings contain high concentrations of arsenic, cadmium, copper, lead, and zinc in a quartz-rich matrix. Most of the waste sites that were sampled had low acid-generating capacity, although one site (fine-grained mill tailings from the Nellie Grant mine deposited in the upper part of lower Frohner Meadows) had extremely high acid-generating potential because of abundant fine-grained pyrite.

Two distinct sites were identified as metal sources based on streambed-sediment samples, cores in the meadow substrate, and mine and mill-tailings samples. The Frohner mine and mill site contribute material rich in arsenic and lead; similar material from the Nellie Grant mine and mill site is rich in cadmium and zinc.

INTRODUCTION

Frohner Meadows is an area of low-topographic gradient subalpine ponds and wetlands about 15 miles west of the town of Clancy, Montana, in the Helena National

Forest (fig. 1). The meadows are located in Frohner Basin, which is in the headwaters of Lump Gulch in the western part of the upper Prickly Pear Creek watershed. Two historical mines, the Frohner and Nellie Grant, are located within the Frohner Basin (fig. 2). Mill tailings, unprocessed ore, and mine-waste dumps at these mines have been eroded, washed downstream, and deposited in Frohner Meadows on lands administered by the Helena National Forest. A mixture of mill tailings and unprocessed ore in Frohner Meadows covers an area of about 8 acres, mostly in the northern or upstream part of the meadows (Metesh and others, 1998). Areas of dead vegetation, as well as areas barren of vegetation, are evident where this waste covers the meadows.

Previous investigations have shown that water containing high concentrations of dissolved trace metals enters the ponds and wetlands from the areas disturbed by mining. Water within Frohner Meadows and runoff from the wetlands contain concentrations of trace metals that exceed aquatic-life and Montana water-quality standards for human health. Dissolved trace-element concentrations in mine runoff are attenuated by the wetlands; however, water and streambed sediment downstream from Frohner Meadows contain cadmium and zinc concentrations that exceed aquatic-life standards for water and consensus-based, probable-effects concentrations for streambed sediment (Klein and others, 2001). Streambed sediment from Frohner Meadows also contains concentrations of arsenic, copper, and lead that exceed consensus-based, probable-effects concentrations (MacDonald and others, 2000).

The U.S. Department of Agriculture-Forest Service (USDA-Forest Service) identified public lands within the Frohner Meadows area that were in need of remediation from historical mining impacts. To develop effective remediation plans for the wetlands and downstream riparian areas, additional information was needed concerning the distribution of metals in mill tailings, meadow deposits, and streambed sediment and the hydrology, hydrogeology, and water quality of the wetlands.

Purpose and Objectives

The purpose of this report is to present data and interpretations from a comprehensive study of the geochemistry of the mill tailings, mine waste, meadow deposits, streambed sediment, and the hydrology and water quality in the Frohner Meadows area. The U.S. Geological Survey, in cooperation with USDA-Forest Service, conducted this study during 2001 and 2002.

Objectives of the study were to (1) characterize physical and chemical properties of mill tailings and transported mine waste in the meadows, (2) characterize the geochemistry of streambed sediment and core samples in the wetlands and waterways of Frohner Meadows and upper Lump Gulch, (3) characterize ground-water flow and quality in the Frohner Meadows area, (4) characterize stream discharge and surface-water quality in Frohner Meadows and upper Lump Gulch, and (5) identify sources of trace metals and quantify loads of trace metals into and out of the meadows. The scope of the study was limited to public lands in Frohner Meadows and upper Lump Gulch that are adjacent to or downstream from the Frohner and Nellie Grant mines.

Description of Study Area

Frohner Meadows consists of two large wetland areas that are referred to in this report as upper and lower Frohner Meadows (fig. 2). A small perennial stream connects two wetland areas. The wetland of upper Frohner Meadows occupies an area of about 14.2 acres, is about 1,670 feet (ft) long from north to south, and is at an altitude of about 6,600 to 6,570 ft. The wetland of lower Frohner Meadows occupies an area of about 15.5 acres, is about 1,750 ft long from west to east, and is at an altitude of about 6,540 to 6,510 ft. Both wetlands contain several inactive beaver ponds that contain water throughout the year. Upper Frohner Meadows receives surface water from several small tributaries. The largest tributary drains into the northwestern part of the upper meadows and informally is named "Frohner Meadows Creek". A smaller tributary enters the western part of the upper meadows and is referred to as "Nellie Grant Creek" (fig. 2). Several tributaries from unmined areas drain from the northern and eastern parts of Frohner Basin into upper Frohner Meadows.

Figure 1. Location of Frohner Meadows study area within the upper Prickly Pear Creek watershed, Montana.

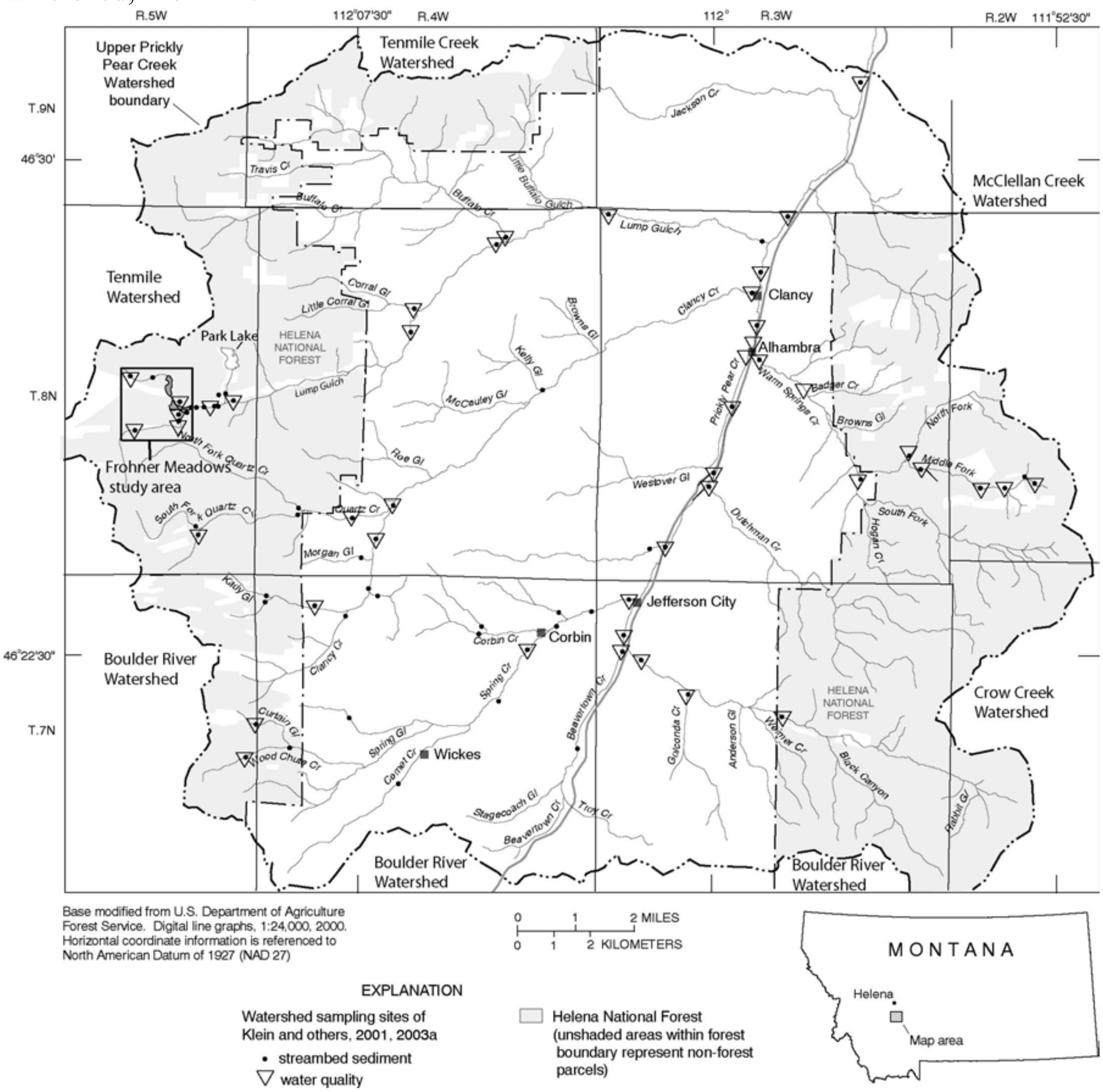
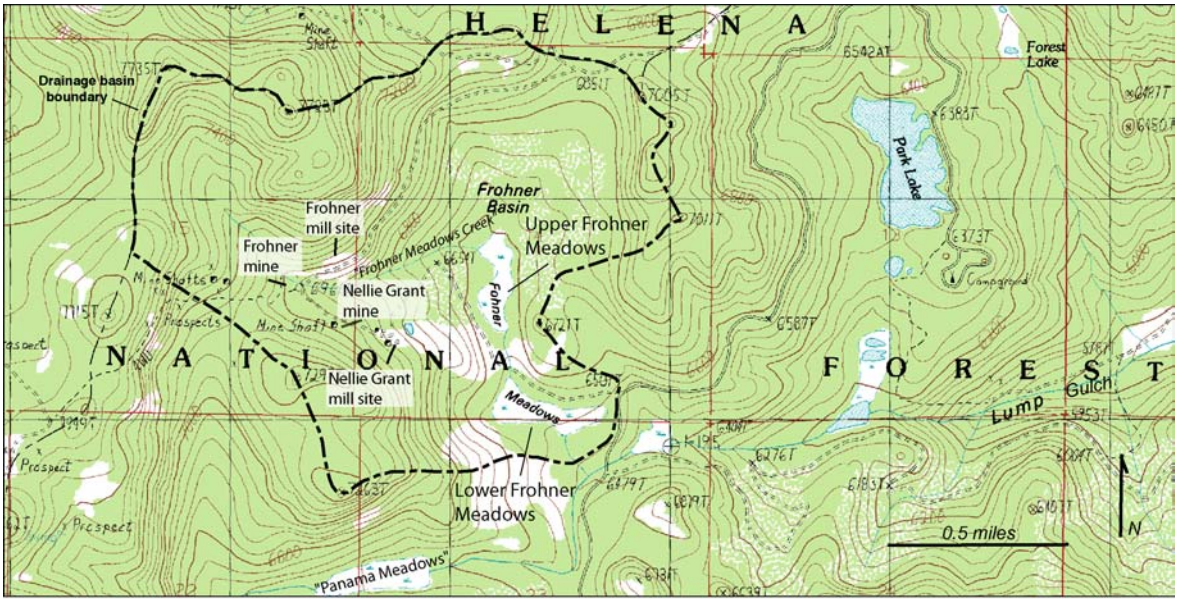


Figure 2. Location of Frohner Meadows study area showing geographic features. Base map from U.S. Geological Survey Chessman Reservoir 7 ½′ topographic quadrangle.



The study area is underlain by granitic rocks of the Boulder batholith (Becraft and others, 1963), which is a very large, composite, late Cretaceous age (80–70 Ma), igneous intrusion that is exposed over an area approximately 30 miles by 60 miles. Near Frohner Meadows, the rocks of the batholith range in composition from quartz monzonite to granodiorite with some small, late-stage aplite or alaskite bodies. Rocks of the Elkhorn Mountain Volcanics, approximately the same age (81–76 Ma) as the Boulder batholith, are exposed about 4 miles southeast of the study area. Small rhyolite intrusions and flow remnants are found throughout the northeastern part of the batholith with the nearest exposure about 1 mile northwest of the study area. Similar intrusive bodies in this part of Montana probably are Eocene-Oligocene in age (37–40 Ma) (Ispolatov, 1997). Rhyolites of the Eocene Lowland Creek Volcanics (53–48 Ma) unconformably overlie exposures of the Elkhorn Mountain Volcanics about 5 miles southeast of Frohner Meadows.

Historical mining activity in the Frohner Meadows area was primarily focused in the area of "Frohner Meadows Creek" and "Nellie Grant Creek" (fig. 2). Base- and precious-metal mining was confined to two principal mines, the Frohner mine and the Nellie Grant mine. These deposits lie along a 5- to 40- ft wide, east-west trending zone (N 70°W, 70–83°S) of quartz and chalcedony veins and hydrothermally altered granitic rocks that is more than 0.5 mile long in sections 14 and 15, T. 8 N., R. 5 W (Becraft and others, 1963). Moderately intense sericitic alteration accompanies mineralization; some clay alteration is present and may be, in part, the result of weathering. Varying amounts of calcite are disseminated in altered rocks and within veinlets in the ore zone.

Ore mineralogy varies between these mines. Ore from the Frohner mine contains a variable but significant amount of galena, sphalerite, and arsenopyrite, with a subordinate amount of pyrite. Pyrite is the most abundant sulfide mineral in the ore from the Nellie Grant mine, which also contains significant galena, sphalerite, and subordinate amounts of chalcopyrite; arsenopyrite was not observed (Becraft and others, 1963).

The Frohner mine was active from the late 1880s to 1954, whereas the Nellie Grant mine was active in the late 1880s through the 1950s and from 1978–1982 (Roby and others, 1960; Pioneer Technical Services, 1996). The Frohner mine consists of at least 2000 ft of tunnels. The extent of underground workings at the Nellie Grant is not known. Incomplete estimates for the Frohner mine (1928–1954) indicated production of 161 troy ounces of gold, 7,329 troy ounces of silver, 2,305 pounds of copper, 91,503 pounds of lead, and 26,000 pounds of zinc from 1,917 tons of ore. The Nellie Grant is reported to have produced 293 troy ounces of gold, 10,279 troy ounces of silver, 3,481 pounds of copper, 216,242 pounds of lead, and 47,156 pounds of zinc from 1,057 tons of ore from 1948 to1957 (Roby and others, 1960).

Two reduction and concentration mill sites are adjacent to the Frohner and Nellie Grant mines (fig. 2). The Frohner mill was originally a gravity-concentration system probably with a stamp mill for crushing; this later was replaced with a flotation system (Roby and others, 1960). Mill tailings and unprocessed ore from this operation were deposited along the adjacent Frohner Meadows Creek in stream terraces, a debris fan in the northwest corner of upper Frohner Meadows, and a large area in the central part of upper Frohner Meadows more than 0.5 mile downstream from the mill. Ore from the most recent milling at the Nellie Grant mine (1978 to 1982) was crushed in a ball mill and concentrated by flotation methods. No information on early ore processing at the Nellie Grant is available. Mill tailings from the Nellie Grant mill are impounded by a small dam on the hillside north of the mill site, buried on the hillside east of the mill site, impounded in a large area in the central part of upper Frohner Meadows, and deposited in a small pond at the west end of lower Frohner Meadows (fig. 2). Reclamation of the Nellie Grant mine site during 1981–1983 and in 1993 consisted mostly of recontouring, controlling ground-water flow to mill tailings, revegetation, and erosion control (Pioneer Technical Services, 1996).

Background data for the Frohner Meadows area were obtained from an inventory of abandoned or inactive mines in the Helena National Forest (Metesh and others, 1998) and from records on file at the Montana Department of Environmental Quality (MDEQ), Helena, Montana. Additional information about site characteristics and reclamation activities at the Nellie Grant and Frohner mines was obtained from reports prepared by Pioneer Technical Services, Inc. (Pioneer Technical Services, 1996, 2000).

GEOCHEMISTRY OF MINE WASTE AND MILL TAILINGS, MEADOW DEPOSITS AND STREAMBED SEDIMENT

Frohner Basin has been the site of several periods of mining for over a century with the activity focused in the area west of upper Frohner Meadows at the Nellie Grant and Frohner mines. Geochemical investigations were undertaken during this study to: 1) chemically and physically characterize the mine waste, mill tailings, and unprocessed ore that has accumulated in Frohner Meadows downstream from the mine areas (fig. 3) and 2) understand the effects of the fluvially transported, ore-related trace metals from these mining-related wastes on the streambed-sediment chemistry throughout Frohner Meadows.

Field methods and sample preparation

Streambed sediment was systematically sampled throughout Frohner Meadows to determine the sources of metals in streambed sediment previously observed at the outlet of the meadows during regional streambed-sediment investigations (Klein and others, 2001), to understand the processes by which metal concentrations in streambed sediment change downstream from the mine area, and to determine the contribution of metals in sediment to the metal budget of the meadow system. Most sites were sampled within a 3-day period during July 2001. This short duration sampling minimized any effects of seasonal variation of elemental concentrations related to changes in stream discharge and water chemistry. Two sites (L-1 and L-2, fig. 3) were resampled in September 2000 when stream discharge was somewhat lower than the July 2001 levels. Sampling and sample-preparation methods for streambed sediment are described in Klein and others (2003b).

Mine waste and mill tailings samples were collected to determine their bulk chemical composition and acid-producing potential. Surface composite samples of mine mill tailings mixed with other mine waste from all but one of the major mill tailings accumulations were collected at five sites (fig. 3). Reclaimed mill tailings at the Nellie Grant mill site were not sampled. Crushed but unconcentrated ore was sampled at two sites (FMB1 and FMB 2, fig. 3). Material from each site was collected and was composited from 30 or more randomly selected cells across the area of the collection site to a depth of about 3 inches. Sampling methods are described in Klein and others (2003b). Data from previous studies of the Frohner and Nellie Grant mine sites data (Metesh and others, 1998; Pioneer Technical Services, 1996, 2000) were used to supplement mine waste and mill tailings data from this study.

Vertical profiles of mill tailings and mine waste accumulations and meadow deposits obtained from cores in wetland areas were used to help determine the thickness and extent of mill tailings and the stratigraphy, physical character, and chemistry of the mill tailings and meadow deposits. Most cores were 2–5 ft deep and were collected along lines at intervals that ranged from 50 to 100 ft. The locations of profile lines and individual sample sites are shown in figure 3. The sampling and sample preparation methods used for cores are described in Klein and others (2003b).

Laboratory Methods

Geochemical samples were analyzed using three different digestion methods that are described in Klein and others (2003b). Resulting solutions were analyzed for 40 elements by inductively coupled plasma-atomic emission spectroscopy (Briggs, 1996). In addition, a fourth digestion method was used to measure net acid-generation potential.

Streambed sediments, surface mine waste and mill-tailings composites, and samples from cores were digested in a mixed four-acid media of HCl, HNO_3, $HClO_4$, and HF. This digestion procedure dissolves most minerals, including silicates, oxides, and sulfides; resistant or refractory minerals such as zircon, chromite; and some tin oxides are only partially dissolved. This digestion, referred to as a total digestion, releases the bulk of each major and trace element contained in a sample. Quality-assurance and quality-control (QA/QC) data for the total-digestion analyses are summarized in Klein and others (2003b, Appendix tables 2a-2c)

Streambed-sediment samples also were analyzed using a dilute HCl-1 percent hydrogen peroxide partial digestion (dilute acid partial digestion) that allows the selective determination of trace-metal concentrations bound within certain specific mineral phases. This digestion releases water soluble and exchangeable metal species from potentially accumulating phases such as hydrous amorphous iron, manganese, and aluminum oxide minerals, with some crystalline iron and manganese oxyhydroxides (Church and others, 1993), and with water soluble, ion exchangeable, and carbonates. QA/QC data for this dilute-acid, partial-digestion is summarized in Klein and others (2003 b, Appendix table 2d)

Surface mine waste and mill-tailings composite samples were analyzed by using the EPA 1312 acidic leach (U.S.Environmental Protection Agency, 1986) and by using a procedure which determines their net acid-generation potential (Lapakko and Lawrence, 1993) and that simulates the net long term or total potential of a material to produce acid over an unspecified period of weathering. The laboratory procedures for these analyses and QA/QC data for the EPA 1312 leach are summarized in Klein and others (2003b, Appendix table 2e).

Mine Waste and Mill Tailings

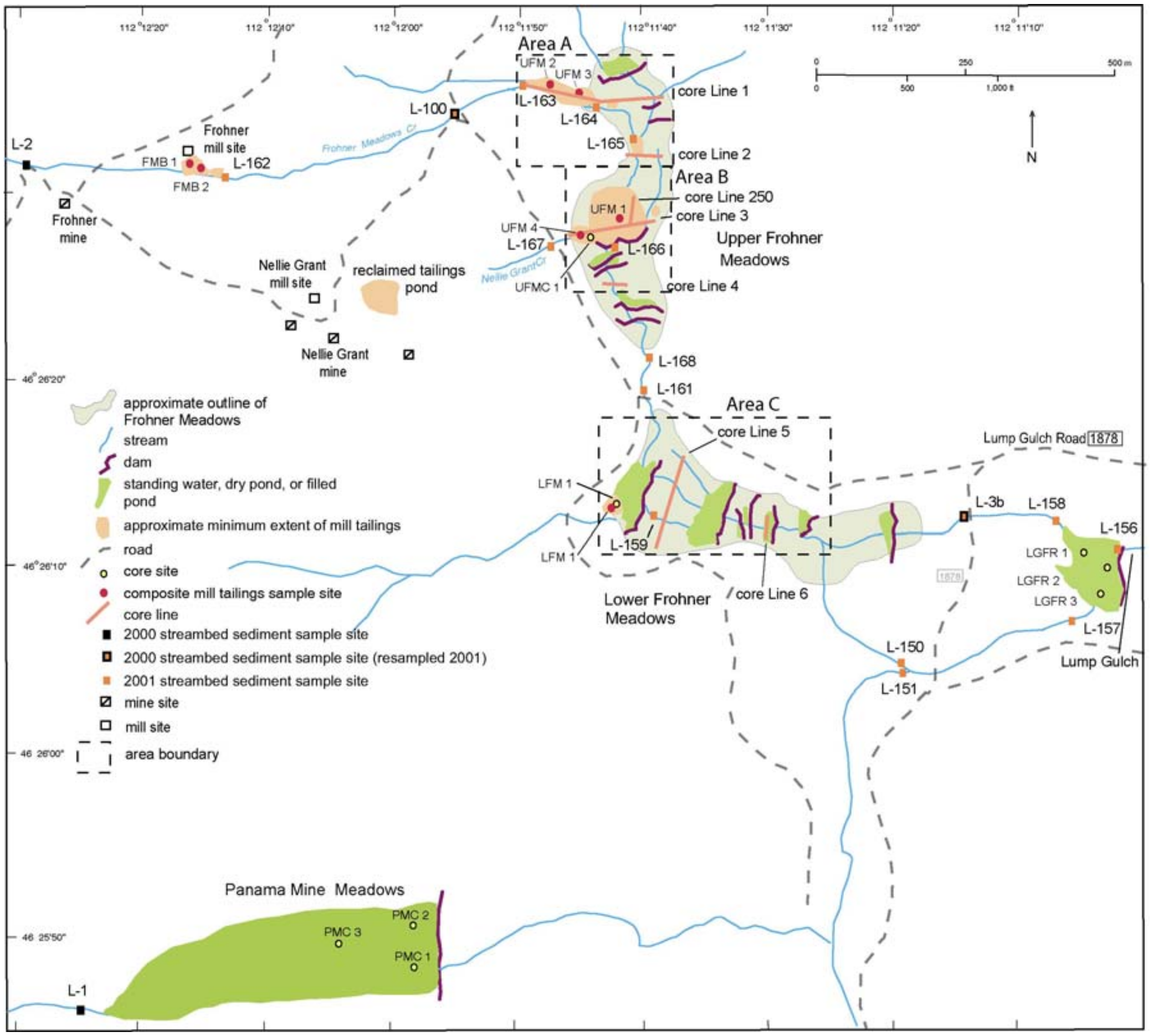
The Frohner and Nellie Grant mine areas are the principal sources of mine waste and mill tailings in Frohner Meadows. A mill was located near each mine (fig. 3), and each produced tailings that have accumulated along Frohner Meadows and Nellie Grant Creeks. Enrichments of the potentially toxic metals–arsenic, cadmium, copper, iron, lead, manganese, and zinc–have been found in previous studies of mine waste and mill tailings at the Nellie Grant and Frohner mines (Pioneer Technical Services, 1996, 2000).

Below the Frohner mill, tailings were deposited along Frohner Meadows Creek upstream from the meadows in small stream terraces and in a mill-tailings debris fan at the change in slope where the stream enters upper Frohner Meadows. Mill tailings have been widely distributed below this debris fan (fig. 3, Area A) by Frohner Meadows Creek in the upper part of upper Frohner Meadow. A substantial amount of mill tailings also was transported by the stream to the mill tailings impoundment in the middle of upper Frohner Meadows (fig. 3, Area B).

Mill tailings from the Nellie Grant mine were impounded in a tailings pond (fig. 3) on the hillslope above upper Frohner Meadows, but some also apparently were transported into upper Frohner Meadows by Nellie Grant Creek. Some mill tailings from the Nellie Grant mine also were discharged into a beaver pond in lower Frohner Meadows (Pioneer Technical Services, 1996) during the latest period of mining (1979–82).

Seven composite surface samples from mill-tailings accumulations in upper and lower Frohner Meadows were collected to determine the chemical composition and acid-producing potential of the tailings. These samples were collected from each of the three major mill tailings accumulations–at the west edge of the Frohner mill-tailings debris fan (Area A), the main mill-tailings impoundment (Area B), and the mill-tailings delta in the western margin of lower Frohner Meadows (fig. 3). Chemical analyses of samples of mill tailings from shallow cores (Klein and others, 2003b) described in the section "Meadow Deposits", that were collected in areas of major mill-tailings accumulations also were used to investigate the chemical variation between mill-tailings sources. Two samples were also collected from dispersed untreated ore at the Frohner mill site (fig. 3, Area A). Data from previous studies of the Frohner and Nellie Grant mine sites (Metesh and others, 1998; Pioneer Technical Services, 1996, 2000) were used to supplement mill tailings and mine waste chemical analyses obtained during this study. Selected analyses from the previous studies, as well as the results of the total digestions analyses of the composite samples from this study, are summarized in Klein and others (2003b).

Figure 3. Location of streambed sediment, individual core, and composite mill tailings sample sites and core lines in Frohner Meadows and upper Lump Gulch.



Some variation in composition of mill tailings and mine waste at these two mine sites is apparent. A ternary plot of arsenic, lead, and zinc concentrations, using data from surface mine waste and mill tailings and the mill tailings collected in cores (tables 6 and 7, Klein and others (2003b), illustrates the compositional variability of mine waste and mill tailings (fig. 4). The position of each point is the proportion of each metal to the total concentration of the three metals found by dividing the concentration of each metal by the total concentration of the three metals. These three ore-related metals illustrate the variability well, because copper is a minor constituent of the ores at the Frohner and Nellie Grant mine and because the chemical behavior of cadmium is nearly identical to that of zinc. These three metals also are highly enriched in streambed sediment in Frohner Meadows and upper Lump Gulch. Unprocessed ore and mine waste from the Frohner mill are distributed near the lead axis with a range of arsenic/(lead + arsenic) of 0.25 to about 0.75; the proportion of zinc to the total of the three metals in these samples is very low (0.05 or less). Waste rocks from the Nellie Grant mine have lower arsenic/(lead + arsenic+zinc) than most of the unprocessed ore samples from the Frohner mill and waste rock from the Frohner Mine, ranging from approximately 0.05 to 0.25. The proportion of zinc to the total-metal content in the Nellie Grant Mine waste is similar to that found in the unprocessed ore and mine-waste from the Frohner mill and mine waste samples. The area labeled mine waste and ore in figure 4 is defined by these samples.

Many samples from Area A below the Frohner mine and mill (fig. 3) plot within the mine waste and ore field (fig. 4) suggesting that they are predominantly transported mine waste and unprocessed ore (fig. 4). Approximately 30 percent of the samples from Area A show high but variable proportion of zinc. These samples are from cores in the most distal part of the deposits that were sampled in Area A; the samples form a group that trends toward the zinc corner of the plot. These samples are composed of sand- and silt-size mill tailings, and their zinc enrichment probably is due to its entrainment in the mill effluent during gravity ore processing at the Frohner mill. Samples from mill tailings in Area B plot in the same area as mill tailings from Area A. Most of the samples of mill tailings from the Nellie Grant mill from the west side of Area B (fig. 3), from the Nellie Grant mill tailings pond (now reclaimed), and from one sample in lower Frohner Meadows are similar to most mill tailings from the other accumulations in Frohner Meadows (fig. 4). One sample plots in the mine waste and ore field and probably is from waste deposited with tailing material. The mill-tailings field is defined by these samples where they lie above the maximum zinc proportion found in ore samples and mine waste.

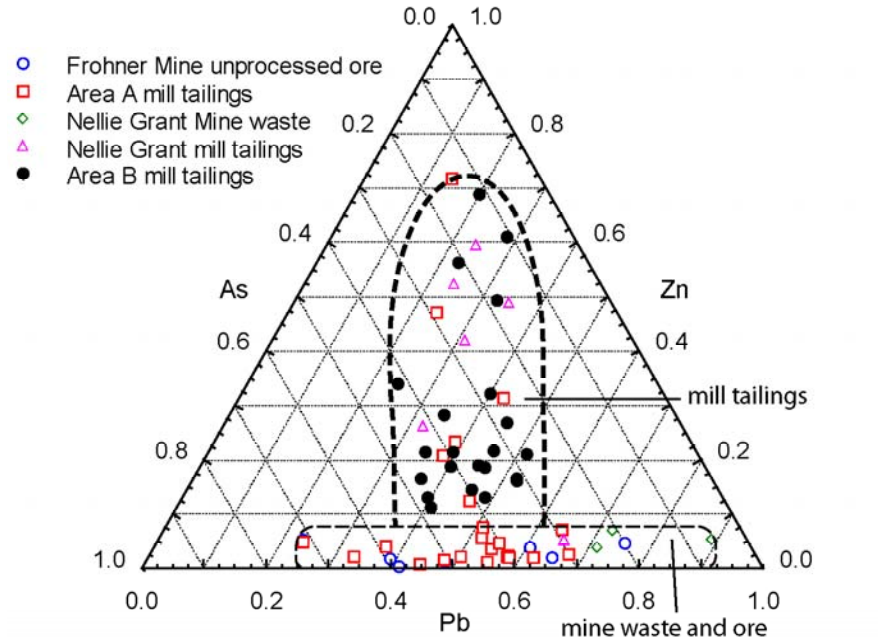
Zinc enrichment, relative to mine waste and unprocessed ore samples, is apparent in many of the surface and core samples from Frohner Meadows. This enrichment is most likely due to the recovery of lead and silver from galena (PbS) and arsenic from either arsenian pyrite (FeS_2) or arsenopyrite (FeAsS) during the extraction process. Zinc from sphalerite (ZnS) was enriched during milling, because it was not recovered efficiently in gravity separation mills such as the Frohner mill. Zinc recovery only was possible in later mills that used the flotation process. However, as late as 1982, zinc apparently was still poorly recovered and, therefore, enriched in the mill tailings, even with the flotation processing at the Nellie Grant mill which produced the most recent mill tailings in lower Frohner Meadows (Pioneer Technical Services, 1996).

The arsenic, lead, and zinc ternary plot is useful in defining the provenance of the surface and subsurface samples in Frohner Meadows. Determining whether a sample is predominantly ore and mine waste or mill tailings is useful in predicting which metals might be most likely contributed to surface or ground water and streambed sediment in a given area.

Acid-generating capacity and leachability of mine waste and mill tailings

Two important characteristics of mine waste are the ability to produce acid and release soluble metals. Procedures were applied to the composite mine-waste samples to determine both. The procedure used to determine the potential net acid production (NAP) is described in Klein and others (2003b), where an aliquot of each sample was exposed to a strong (30-percent) solution of hydrogen peroxide. Sulfide minerals (typically mostly pyrite, FeS_2) in the sample are oxidized during the digestion and produce sulfuric acid. The results are expressed in terms of the concentration of calcium carbonate ($CaCO_3$) in kg/metric ton that would be required to neutralize the resultant acid. The result is a net estimate of the total acidity that the sample could produce over an unspecified period of

Figure 4. Ternary plot of arsenic, lead, and zinc total concentrations of mine waste, unprocessed ore, and mill tailings in Frohner Meadows area. The areas referred to are shown in figure 3.



time, as it takes into account the potential neutralization by acid-consuming minerals and the continuous generation of acid as weathering and transport remove previously generated acid. The NAP of a material is the simple difference between its acid-producing potential and its acid-neutralizing potential. This can be determined by separately measuring both attributes in the laboratory and taking the difference or measured on one solution, where the acid is both produced and neutralized by the sample itself as done for this study.

The results of the NAP test show a range of values from 2 to 250 kg/ton (table 1). This procedure has been applied in other studies to mine-waste material from the Boulder River watershed west of Frohner Meadows and material from the Animas River watershed in southwestern Colorado (Fey and others, 2000a; Fey and others, 2000b). Results from 19 samples from the Boulder River watershed ranged from 0 to 34 kg/ton, and results from 110 samples from the Animas River watershed, Colorado, ranged from 0 to 167 kg/ton. Thus, the sample of fine-grained mill tailings from the mill-tailings delta at the west end of lower Frohner Meadows (LFM#1 NGS) has an extremely high NAP. Another measure of the acid-producing qualities of a mine-waste material is known as the "Neutralization Potential Ratio" (NPR), which is the ratio of the neutralization potential to the acid-producing potential, where again each potential is measured separately. There are several ranges of the NPR, and a mine-waste material can be placed into several different categories. According to one classification scheme by Price and others (1997), four different categories can be used relating the NPR to the likelihood of a waste material to be an acid producer. These categories are: NPR < 1, acid production likely; NPR between 1 and 2, acid production possible; NPR between 2 and 4, acid-production potential low; and NPR > 4, no acid production potential. The fourth category can be obtained by mixing a sufficient amount of limestone to a mine waste to achieve a 4:1 ratio. For example, to remediate a sample with a NAP of 10 kg/ton would require mixing in 40 kg/ton $CaCO_3$ into the material or about 170 pounds of limestone per cubic yard. Samples FMB 1 and LFM 1 NGS (table 1) have high NAP values that would make it impractical to apply and to mix limestone onsite: LFM 1 would require over 4,000 pounds of limestone per cubic yard (about a 50 percent mix of limestone with waste). In addition, this site is under water, making it exceedingly impractical to remediate.

All of the other samples, except UFM 2, have relatively low NAP values. This sample was analyzed for acidity on three splits,– the > 2-mm fraction, the < 2-mm fraction, and a combined bulk fraction. In most geochemical studies, the finer-size fractions contain more of the constituents of interest (Horowitz and others, 1991). This was not the case for acidity and UFM 2. The > 2-mm fraction yielded an NAP value more than 10 times higher than the < 2-mm fraction, and more than 2 times as high as the bulk fraction. This sample contained coarse, angular, quartz chips that are interpreted to be coarsely ground ore material. The coarse grinding did not fully liberate pyrite and other sulfide minerals;

Table 1. Net acid-producing capacity of mine waste and mill tailings (kg/ ton $CaCO_3$).

sample number	description	acid-producing capacity
FMB 1	Frohner mill, composite ore sample	38
FMB 2	Frohner mill, composite ore sample	7.2
LFM 1 NGS	lower Frohner Meadows, Nellie Grant mill-tailings delta	250
UFM 1	upper Frohner Meadows, mill-tailings debris fan, eastern part, bulk	3.1
UFM 2 BULK	upper Frohner Meadows, mill-tailings debris fan, western part, bulk	12.8
UFM 2 (>2-mm)	upper Frohner Meadows mill-tailings debris fan, western part, +2 mm fraction	35
UFM 2 (<2-mm)	upper Frohner Meadows, mill-tailings debris fan, western part, -2 mm fraction	2
UFM 3	upper Frohner Meadows, main mill tailings area	4.3
UFM 4	upper Frohner Meadows, Nellie Grant mill-tailings fan	2.8

however, the sample preparation process for this study (grinding to < 200-mesh) allowed all pyrite to be available for reaction in the acidity determinations. Thus, the NAP value obtained from the >2-mm fraction is a high estimate for the total potential of the > 2-mm fraction to create acid. The value obtained from the < 2-mm fraction, only 2 kg/ton, indicates there were few acid-storing soluble salts or pyrite in the fine fraction. The bulk sample yielded a value (12.8 kg/ton) between that of the < 2mm and the > 2-mm fractions. When all three fractions were subjected to the EPA-1312 leach (see below), they produced leachates with a pH between 3.5 and 3.7. The pH of the leach solutions represents a snapshot of the hydronium-ion activity, whereas the NAP represents the long-term potential for acidity.

The leachability of various constituents from the composite mine waste and mill tailings samples was determined using the EPA-1312 procedure (SLP) described in Klein and others (2003b). This procedure simulates the effect of rainfall or runoff on a dump surface. Note that in the discussion below, the term "leachable" applies to constituents liberated by the SLP test solution, which is deionized water acidified to pH 4.2 and not those liberated by the dilute-acid partial digestion that was applied to streambed sediment. The ore-related metals analyzed in the leachate were arsenic, cadmium, copper, lead, and zinc. When the sum of the concentrations of these five metals in the leach solution is plotted against the NAP value obtained from the acidity test (fig. 5), the plot provides a geochemical rank of each waste and tailings source, which should be considered with other factors to determine what remediation action is appropriate. Other factors that could be considered include the amount of material, proximity to flowing water, permeability of the substrate, and slope aspect.

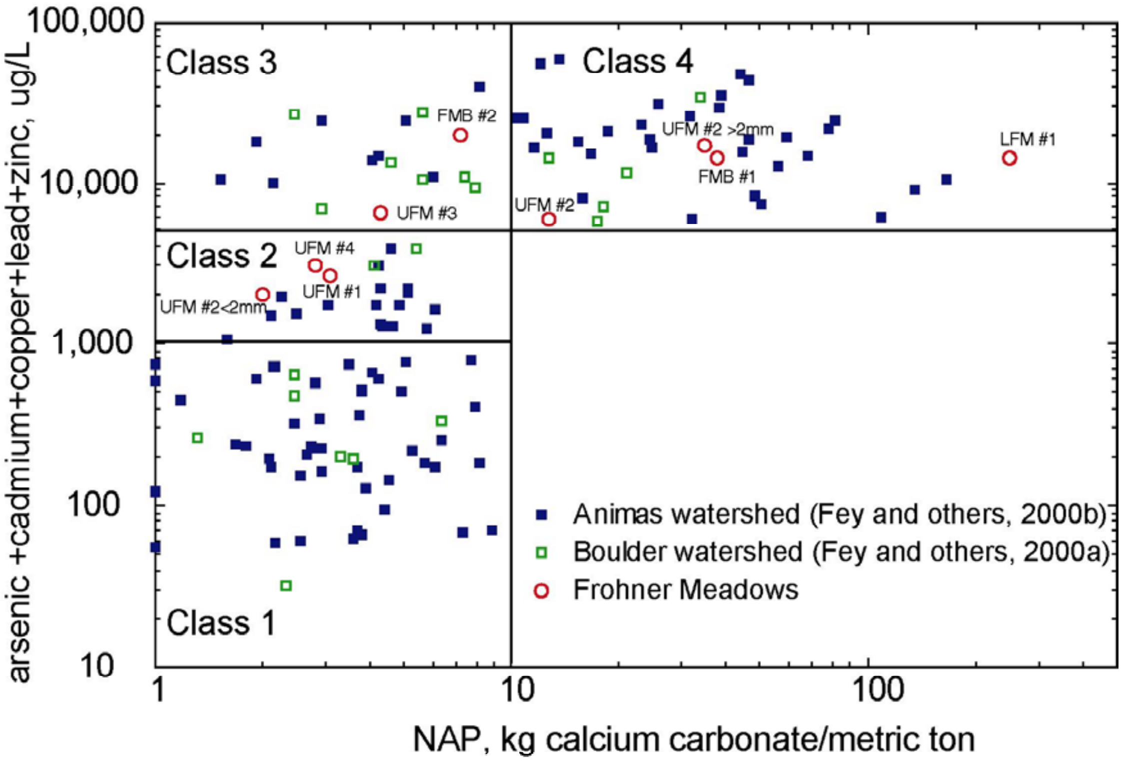
The diagram in figure 5 is divided into four geochemical classes based on the classification of Fey and others (2000c). Class 1 contains material that generates little acid (< 10 kg/ton $CaCO_3$) and produces low concentrations of leachable metals (< 1,000 μg/L summed metals). Class 2 is material that produces low acidity and moderate summed leachable metals. Class 3 consists of material with low acidity but high concentrations of summed leachable metals. Class 4 contains material that produces high acidity and high concentrations of leachable metals (> 10 kg/ton $CaCO_3$ and > 5,000 μg/L summed leachable metals). With other factors being equal, mine waste and mill tailings scoring in Class 4 would be of the highest concern, whereas these materials in Class 1 would rate lowest in concern.

Two composite unprocessed crushed-ore samples were collected at the Frohner mill site (fig. 3). Sample FMB 1 was collected from the ground below the mill, and FMB 2 was collected from an above-ground bin. Both samples yielded SLP leachates with similar geochemistry (Klein and others, 2003b) where the leachates had summed dissolved-metal concentrations dominated by lead (13,000 and 19,000 μg/L summed leachable metals, respectively). However, the NAP values obtained from the two samples are different. Sample FMB 1 had an NAP value of 38 kg/ton $CaCO_3$, whereas sample FMB #2 had an NAP value of 7 kg/ton $CaCO_3$. This difference may relate to the composition of source material or differences in their response to weathering. Regardless of the acidities, both unprocessed ore samples produced leachates with high dissolved-metal concentrations.

Sample UFM 1 was collected at the upper (western) end of fluvial-mill tailings deposited in Frohner Meadow Creek as it entered upper Frohner Meadows (fig. 3). This sample produced a moderate 2,700 μg/L summed leachable metals. The NAP value was low (3.1 kg/ton $CaCO_3$), indicating that little pyrite was present to produce acid.

Sample UFM 2 was collected from Area A (fig. 3) and was separated into three size-related subsamples as described in the previous section (acid-generating capacity). The results from the acidity and SLP tests show a distinct difference between the size fractions. The bulk sample plots in Class 4 of figure 5. The >2-mm-size fraction plots in

Figure 5. Comparison of acid-generating capacity and ore-related metal yields of mine waste and mill tailings from Frohner Meadows with other mine sites.



Class 4, whereas the <2-mm-fraction plots in Class 2. These mill tailings probably were processed by an early stamp mill and contained many coarsely crushed quartz chips. Despite being contained in coarse chips, the coarse fraction produced a high concentration of lead (17,000 µg/L) and a low concentration of zinc (330 µg/L). The sample of <2-mm material produced only 1,300 µg/L lead and a slightly higher zinc concentration of 570 µg/L, indicating that the coarse fraction mill tailings was the source of the high amounts of metals and acidity found in the bulk sample.

Sample UFM 3, which contains some fluvial-mill tailings similar to the coarse-grained material in sample UFM 2, was collected over a relatively large area upstream from UFM 2 in the main mill tailings area of Area A in upper Frohner Meadow (fig. 3) from overbank material that was transported down Frohner Meadows Creek. The summed dissolved metals (6,500 µg/L, dominated by zinc) placed this sample in Class 3. This sample also produced the second highest concentration of dissolved cadmium (73 µg/L).

Sample UFM 4, collected from the mill tailings debris fan on Nellie Grant Creek on the west side of upper Frohner Meadow that drains the Nellie Grant mine area, produced a leachate with the lowest pH and highest specific conductance of all the samples. However, the summed dissolved metals was moderate (3,200 µg/L, dominated by zinc), and the net acid production was the second lowest. This material probably has a higher proportion of soluble salts and a lower concentration of pyrite than the others.

Samples LFM 1, from the fine-grained mill tailings in the delta from the pond in lower Frohner Meadows (area C, fig. 3), produced a leachate with the highest arsenic, cadmium, and zinc concentrations (900, 170, and 9,100 μg/L, respectively) of the samples from the study area. This material is probably a source for some of the solution-transported arsenic enrichment observed downstream in streambed sediment at site L-159 (see below).

Meadow Deposits

Frohner Meadows is covered by thick vegetation, many shallow beaver ponds, and fine-grained pond-fill deposits that now are exposed in breached beaver ponds. Mill tailings have been impounded behind several beaver ponds; many areas that contain a substantial thickness of mill tailings are obvious from their lack of vegetation. However, in some areas where vegetation is thick, mill tailings often are concealed by thin, organic-rich soil and are difficult to identify. In some ponds where water levels have decreased due to breaches in inactive beaver dams or from low water flow, fine-grained pond-bottom deposits commonly are difficult to discriminate from transported fine-grained mill tailings.

A reconnaissance coring program was undertaken throughout Frohner Meadows to determine (1) the stratigraphy of the meadow deposits including exposed tailings, (2) the extent, thickness, and chemical composition of buried mill tailings, and (3) the degree of post-deposition subsurface metal migration. A total of 27 cores were collected in upper Frohner Meadows and a total of nine were collected in lower Frohner Meadows. Three cores were also taken in meadow deposits in a nearby valley, referred to informally as the Panama Mine Meadows (fig. 3). This area has had no obvious significant mining or milling activity and was sampled to aid in establishing background concentrations for the study area and to determine the origin of the deposits filling an abandoned reservoir in Panama Mine Meadows. Recovered core lengths ranged from 33 to 133 cm. Core sampling was conducted between July 16 and July 19, 2001. Sampling methods and data from these core samples are discussed in Klein and others (2003b) with the geographic locations and other site data presented in Appendix 1a, core descriptions and location of intervals sampled for chemistry presented in Appendix 1b, and the results of the chemical analyses of the sampled intervals using the total digestion are listed in table 7 of that report.

Premining metal concentrations in Frohner Meadows

Frohner Meadows has been formed from fill material, some of which is certainly locally derived. This fill material, mostly alluvial in origin, in part, may have been derived from streambed sediments that originated from metal-bearing material from the natural exposures of the Frohner-Nellie Grant vein system and weakly mineralized rocks that typically surround these vein systems. The streambed sediment likely would have higher ore-related element concentrations than normal watershed streambed sediment from sites within drainage basins that had little or no impact from mining or known mineral deposits.

Establishing local premining ore-related element concentrations allows the determination of the degree of metal enrichment in postmining streambed and pond-fill deposits from the area drained by Frohner Meadows Creek, the upper part of Lump Gulch Creek and Panama Mine Meadows, and is necessary when establishing baseline concentrations that are relevant in defining remediation goals. Samples from cores that were used to estimate premining concentrations were selected from cored intervals where the intervals appeared to be geologically or geographically isolated from mining-related deposits. These samples were chosen from areas that contain no physical signs of previous mining activity (Panama Mine Meadows) and(or) from core intervals below mine waste and mill tailings that are separated from them by thick clay layers. The samples used to define the premining metal concentrations in Frohner Meadows and their chemical analyses are tabulated in Klein and others (2003b).

Two types of deposits encountered in the cores in Frohner meadows were clay-rich deposits and coarse-clastic deposits. Clay-rich deposits formed during sedimentation that resulted in the infilling of shallow ponds and marshes. Sandy or coarse alluvium formed in stream channels or as overbank deposits along paleostream channels. Geochemically, the postdepositional environment of these two types of deposits may differ because of the physical and hydrological character. In order to determine if background concentrations differ in these two environments, metal concentrations encountered in clay-rich samples were compared statistically with those from coarse-clastic deposits.

The population distributions of the metals arsenic, cadmium, copper, lead, and zinc were compared with calculated normal distribution curves, and all except zinc were nonnormally distributed. The nonparametric Mann-Whitney U test was used to compare the metal populations from these two sample types. This test provides a rigorous comparison between two nonnormally distributed populations and works equally well on those that are normally distributed. The results of this test indicate that the metals concentrations of both groups are statistically similar ($p<0.05$) and can be combined to estimate premining concentration levels. A summary of the descriptive statistics for background samples from the two groups is shown in table 2.

Table 2. Means and standard deviations for ore-related metal concentrations in core samples used to define premining conditions in the study area. All concentrations are total.

[Frohner Meadow geochemical threshold is the premining concentration plus 2 standard deviations. Mean global sediment and soil concentrations are from Bowen (1979). Boulder River concentrations are from Church and others (in press). Cadmium concentrations below detection limit (2 ppm) in Frohner Meadows were assigned a concentration of 1 ppm for calculating the mean. All concentrations are in parts per million; standard deviations are in parentheses]

Metal	Frohner Meadow premining concentration	Frohner Meadow geochemical threshold concentration	Boulder River watershed pre-mining concentration	Global sediment	Global soil
arsenic	58 (32)	122	58 (57)	8	6
cadmium	2.2 (1)	4.2	<2 (-)	0.05	0.35
copper	42 (21)	84	59 (32)	33	30
lead	114 (86)	286	79 (55)	19	35
zinc	232 (67)	366	159 (52)	95	90

Trace-element chemistry of streambed sediment and other geologic materials were investigated in the nearby Boulder River watershed (Church and others, in press). The Boulder River watershed lies immediately west of the upper Prickly Pear Creek watershed which contains the Frohner Meadows study area. The Boulder and Prickly Pear Creek watersheds are similar in bedrock geology, glacial history and contain similar mineral deposit types

As part of the Boulder River watershed study, 16 sites were sampled to determine premining metal concentrations in streambed sediment and terrace deposits downstream from areas that were mined or mineralized; the means and standard deviations of the Boulder River data are shown in table 2 for comparison with the premining samples of meadow-fill deposits in the Frohner core samples. Concentrations of lead and zinc in Frohner Meadows background samples are substantially higher than background samples in the Boulder River watershed and mean-global soil and sediment concentrations, whereas arsenic and copper concentrations are similar to the Boulder River watershed concentrations and substantially higher than the mean-global soil and sediment concentrations. A comparison of the metal concentrations of the Frohner Meadows and Boulder River watershed premining samples, using the Mann-Whitney U test, shows that the populations of arsenic, cadmium, and copper concentrations are similar, and lead and zinc concentrations are dissimilar at $p<0.05$. These results strongly suggest that locally derived premining metal concentrations should be used for the Frohner Basin. Arsenic concentrations in these samples are high relative to global-mean sediment and soil concentrations but similar to the Boulder River watershed premining background, suggesting that a regionally high arsenic background is present in both watersheds.

Calculation of geochemical threshold concentrations is a commonly used technique in exploration geochemistry that allows definition of anomalous samples. Geochemical threshold concentrations presented in table 2 were calculated from the cores by using the mean concentration of each metal plus 2 standard deviation concentrations, which is a commonly accepted method (Rose and others, 1979). These threshold values are used to identify sample intervals in Frohner Meadow cores that have metal concentrations which are likely to be truly anomalous (enriched) and not merely in the upper range of the "normal" values.

Postdeposition metal migration

Vertical chemical profiles were plotted for several cores to investigate the vertical variation in metals and related elements. These plots revealed two types of profiles. The first, illustrated by site UFMC-1-150 from the western part of line 1 (fig. 3), and the second illustrated by site UFMC-3-250.

At site UFMC-1-150, a coarse mixture of oxidized fluvial-mill tailings, unprocessed ore or mine waste, and transported colluvial granitic material (slope wash) overlie a thin meadow "soil" consisting of a mixture of peat, silt, and fine tailings. The lower part of the core is an interval of interlayered alluvial and transported granitic alluvial and colluvial deposits (fig. 6). The chemical profile of this core shows high concentrations of one group of metals (arsenic, copper, iron, and lead) in the upper two samples (mill tailings and mine waste) with concentrations lower and declining in the underlying transported colluvial material, meadow "soil", and the mixed layer of transported colluvium and alluvium (fig. 6). The highest concentrations of this first group of metals have levels similar to ore from the Frohner mine. Concentrations of a second group of metals (cadmium, manganese, and zinc) are lowest in the upper two sample intervals; the concentrations of these metals generally increase with depth from 26.5 cm to approximately 64 cm. Cadmium, manganese, and zinc concentrations also are typically high in local unprocessed ore and mine waste and would, therefore, be expected to be high in mill tailings as seen in bulk samples from the study area (table 6, Klein and others, 2003b). However, the concentrations of these three metals generally are lower in the mill tailings in the upper part of this profile than in the underlying deposits. The difference in the profiles of these two groups of metals can be explained by their chemical behavior during weathering and the mixing of ore-related material (mill tailings, ore, and mine waste) with geologic material with background-metal concentrations.

Geochemically, arsenic, iron, and lead are relatively immobile after weathering and oxidation of the sulfide ore minerals, and their abundance in the profile is related to their original concentrations in the mill tailings; reduction in their concentrations can be primarily attributed to mixing with geologic material having background-metal concentrations. Cadmium and zinc are geochemically mobile in oxidizing environments; they have moderate concentrations at the top of this profile and increase with depth. This increase probably is the result of oxidation of sulfide minerals in mill tailings and mine waste and dissolution of these metals in the upper parts of the profile during weathering and subsequent deposition and concentration at deeper levels by precipitation or sorption from downward percolating water or laterally transported by water in permeable subsurface material. Copper shows relatively little change through the profile. All of these metals show a marked reduction in their concentrations in sample UFMC-1-150c (28 cm) that probably is due to dilution by a large amount of transported granitic colluvium.

Contrasting geochemical behavior is shown in the core from site UFMC-3-250 near the middle of line 3 (fig. 3). This core consists of oxidized fluvial-mill tailings that overlie a relatively thin layer of reduced, bedded, fine-grained mill tailings (fig. 7). These mill tailings overlie clay-rich, highly organic premining pond-fill deposits and fluvial deposits. The highest concentrations of arsenic, cadmium, copper, lead, and zinc occur in the reduced mill tailings (fig. 7). The addition of fluvial material with background metal concentrations acting as a dilutant causes lower concentrations of arsenic, cadmium, copper, lead, and zinc in the uppermost sample interval relative to the generally high concentrations seen in fluvial-mill tailings found along core line 1 (Klein and others, 2003b). Below the reduced mill tailings in 3-250, concentrations of all metals are substantially lower in the deep-fluvial deposits, and there is no apparent postdeposition mobility of any metals including cadmium, copper, manganese, and zinc such as that observed at site UFMC-1-150 (fig. 6).

The contrasting behavior of cadmium, copper, and zinc at these two sites is probably due to the difference of oxidation-reduction characteristics in the upper parts of the two cores. In core 1-150, downward percolating or laterally flowing surface water is thought to have substantially oxidized the tailings during weathering and mobilized cadmium, copper, and zinc.

The solubility of the geochemically mobile metals (cadmium, copper, and zinc) is highest under oxidizing conditions, resulting in their migration into underlying material. These effects of weathering are enhanced by the porous nature of the underlying material that allows rapid percolation of surface water through the mill tailings and the position of the mill tailings relative to the local ground water, which is well below these deposits. In core UFMC-3-250, the upper parts of the deposits mostly are oxidized fluvially-transported mixed mill tailings and mine waste probably are from the same source as those from line 1 (fig. 3) upstream from line 3, as suggested by the abundance of coarse quartz chips. These are mixed with a small amount of silty, reduced mill tailings that probably from a local source. The profiles of the three mobile metals (cadmium, copper, and zinc) are similar to those of the relatively immobile metals (arsenic and lead), suggesting that there has been little postdepositional migration. The conditions in this area are substantially different than those at the site UFMC-1-150. Shallow ground water in this area results in near-surface reducing conditions that are not conducive to a high degree of solubility of cadmium, copper, and zinc. The presence of low-permeability material underlying clay-rich pond fill and the organic-rich nature of the pond fill deposits also may form a physical and chemical barrier to metal migration.

Upper Frohner Meadows

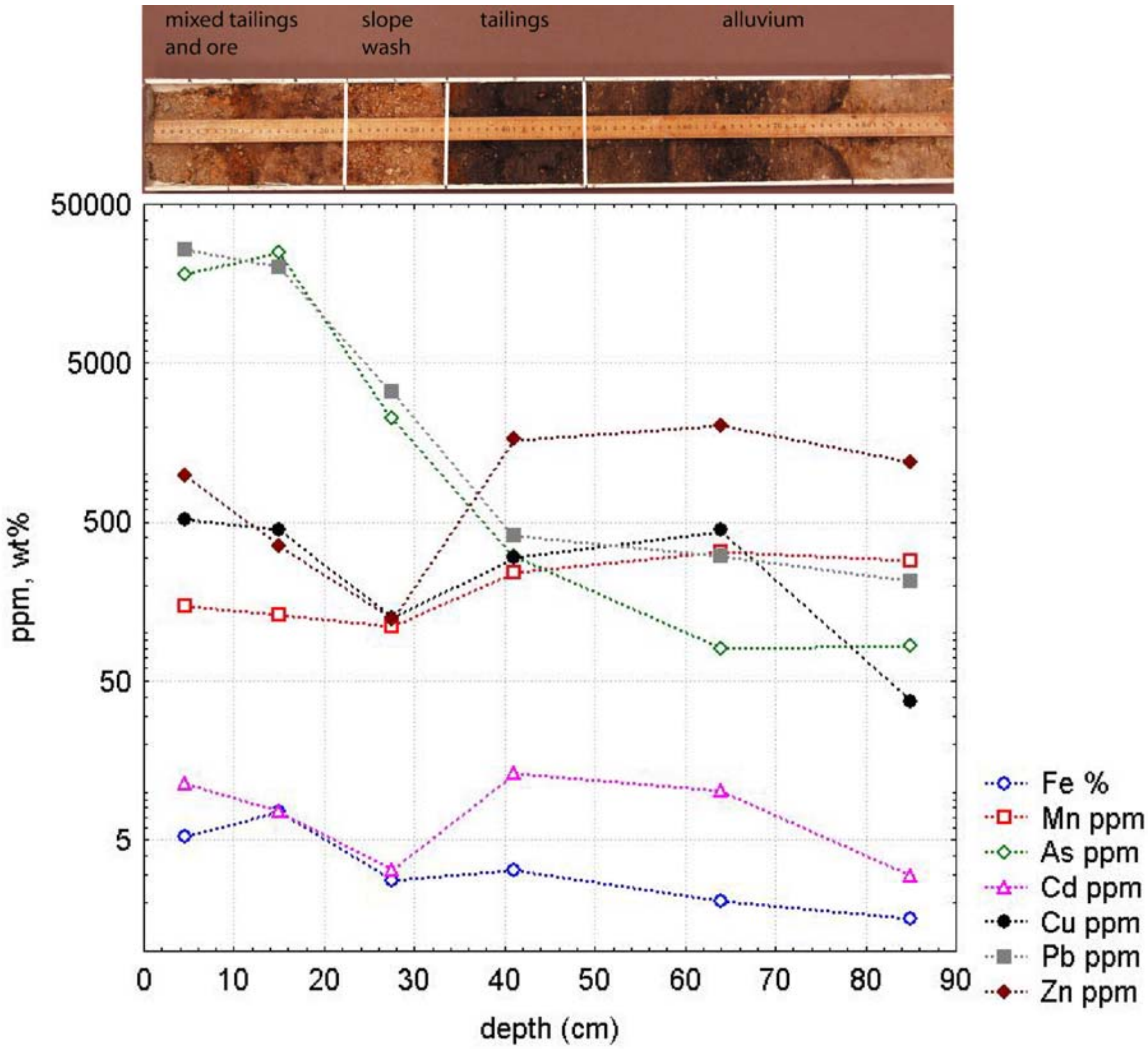
Mill tailings are concentrated in two areas in upper Frohner meadows – a debris fan of fluvial material and mill tailings where Frohner Meadows Creek enters the meadow at Area A (fig. 3) and in a large impoundment that is in Area B directly east of the Nellie Grant mine area that is contained behind a sinuous beaver dam.

Area A

The debris fan and the portion of the meadow that lie to the east were sampled along a longitudinal core line at intervals of 40 to 100 ft (fig. 8). Sites and samples along this line are designated with the prefix of 1. Twelve sites were cored along the line; eight cores were chosen for chemical analysis (fig. 8) from which 31 intervals were sampled. Descriptions of the core samples and the geochemistry for these samples are in Klein and others (2003b). A typical cross section is exposed in the bank of Frohner Meadow Creek, where it has cut through the western part of the debris fan (fig. 9). Mill tailings and associated coarse-grained quartz fragments overlie a thin layer of clay-rich fine-grained mill tailings, which in turn, overlie a sequence of fine- to medium-grained stream deposits and thin organic-rich clay layers that probably were formed in shallow ponds or wetlands. Samples from core samples that exceed the geochemical threshold (table 2) for any of the five metals will be referred to in the following sections as enriched material based on the chemical analyses in table 7 of Klein and others (2003b). The mean-minimum thickness of enriched material encountered in the sampled cores along line 1 is 64 cm; the greatest thickness is at site 1-150 where enriched material is greater than 111-cm thick (fig. 8). The thickness of enriched material is greater than that of actual mill tailings at many sites because adjacent nontailings deposits may have been enriched in metals by their redistribution from the mill tailings by infiltrating surface water during weathering. Thin soils (less than 8 cm) typically overlie these deposits. The stratigraphy of the cored material changes between sites 1-250 and 1-300, where fine-grained mill tailings are deposited directly over clay-rich pond deposits rather than over alluvium; similar relations are observed in all cores that lie east of that site. In several cores, several sequences of pond deposits are interlayered with medium- to coarse-grained alluvium. Enriched material at site 1-600 is 35-cm thick; no coarse-grained mill tailings were observed at sites 1-600 or 1-700.

Core line 2 is located 300 ft downstream from line 1 (fig. 3). Three sites were sampled perpendicular to the long axis of the meadow from which a total of nine intervals were sampled. Enriched material at sites 2-0 and 2-60 (fig.8) are 55- and 78-cm thick, respectively and thins between site 2-60 and 2-130 to 9 cm. Enrichment at site 2-130 is marginal with zinc at 380 ppm that is only slightly above the threshold value of 340 ppm. Enriched intervals in this area range directly overlie pond deposits at all sites. Soils are from 8- to 17-cm thick along this core line.

Figure 6. Composite image and geochemical profile of core UFMC 1-150 showing the relation between stratigraphy and chemistry. Depths are uncorrected for compaction.

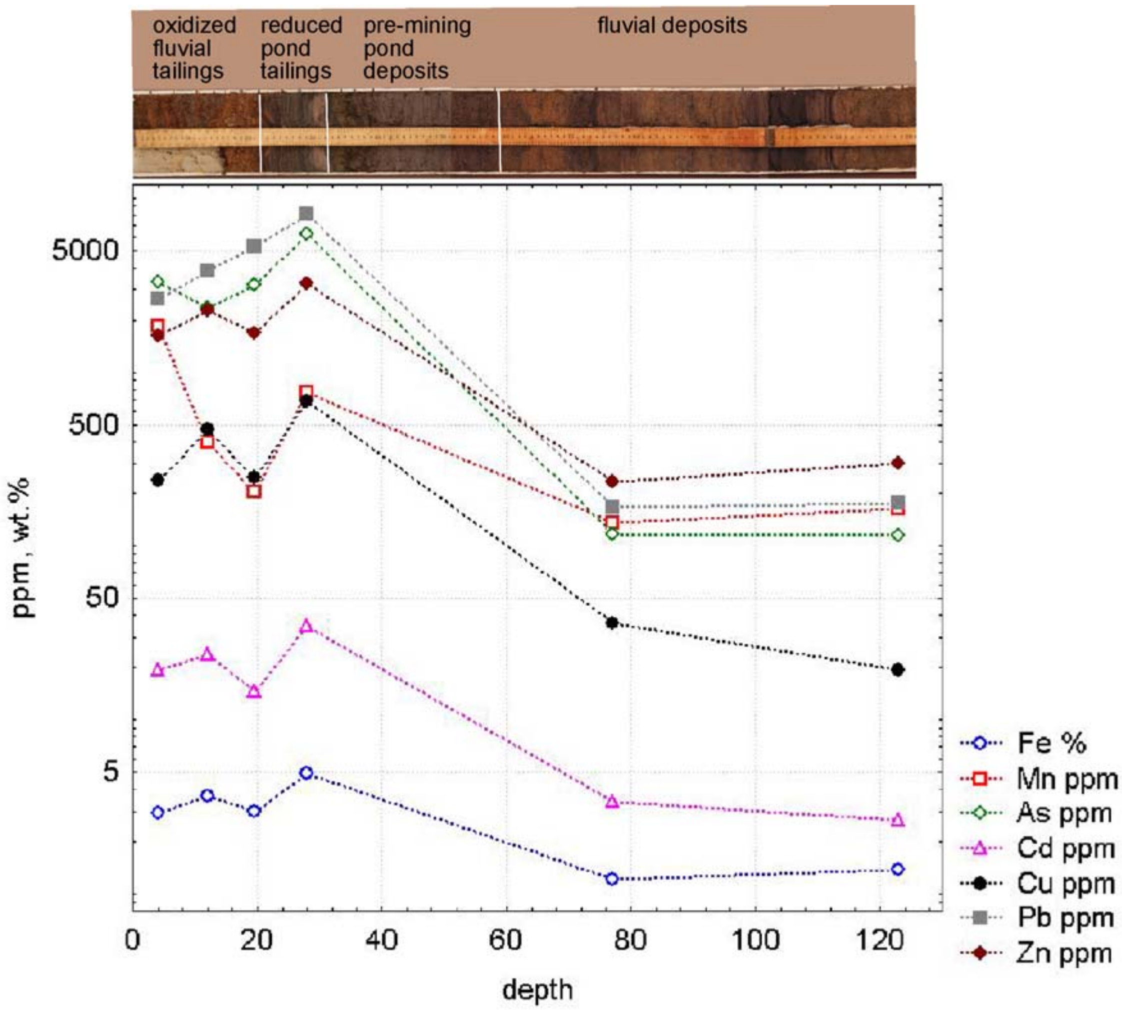


Because ore-related metal concentrations are highly variable within individual cores, the geochemical data in each core were vertically integrated by calculating a weighted average based on the thickness of the analyzed intervals to allow comparison of the bulk compositions of enriched material between sites. Each sample was assumed to represent the composition of the entire stratigraphic unit in which it was found. The weighted-average concentration (WAC) used to integrate the metal concentrations was calculated using the formula:

$$WAC = \Sigma\,(\text{thickness of sampled interval} \times \text{metal concentration of interval}) / \Sigma\ \text{thickness of sampled intervals}$$

The WAC calculated for the ore-related metals from cores in Area A (fig. 3) is shown in figure 10. In the following sections, slight enrichments are defined as those that are from 1 to 5 times the premining background concentration for each metal; moderate enrichments are those greater than 5 and greater than or equal to 10 times the premining background

Figure 7. Composite image and geochemical profile of core UFMC 3-250 showing the relation between stratigraphy and chemistry. Depths are uncorrected for compaction.



concentration for each metal; and high enrichments are those greater than 10 times the premining background value for a given metal.

All cores in line 1, from 1-0 to 1-500 inclusive, and core 2-0 show high WAC values of arsenic, cadmium, and lead. Zinc and copper enrichments are moderate. Enrichments of most metals in samples from 1-600, 2-60 and 2-130 are slight, or they are near premining background concentrations although cadmium concentrations in 2-60 is highly enriched. The lower WAC concentrations for all metals at sites 1-600 and 2-130 are probably due to dilution of the enriched material with material with lower metal concentrations from sources east of and north of the meadow.

Area B

A large volume of exposed mill tailings is in Area B (fig. 3) in Upper Frohner Meadows directly east of the Nellie Grant mine. Samples were taken along two core lines in this area of mill tailings; line 3 is perpendicular to the length of the meadow, and line 250 is located along a line with a bearing of N 12° E from sample site 250 on line 3, roughly parallel to the length of the meadow (fig. 11). Six sites were sampled along line 3 at 50 to 100 ft intervals, and two samples were taken along line 250, 75 ft and 200 ft north of line 3. An additional sample (UFMC 1) is southeast of site 3-0 near the toe of a debris fan at the outlet of Nellie Grant Creek.

The thickness of enriched material ranges from 33 to 88 cm with a mean of 62 cm. Mill tailings that are exposed in a shallow incised channel in the center of the meadow are interlayered oxidized silt and fine sand-size mill tailings and coarse quartz chips (fig. 12), similar to the material observed along line 1 (fig. 9). The character of the surface mill tailings changes from the middle of this area where they are interlayered coarse-grained and fine-grained material to the margins of the meadow where they are fine- and medium-grained well-sorted sand. The greatest thickness of the metal-enriched material is at sites 3-0, 3-100, and 3-300 (fig. 11). Mill tailings at sites 3-100 and 3-200 are mostly silt- and clay-size, whereas at sites UFMC 1, 3-250, 3-300, 250-75, and 250-200 sand-size mill tailings of varying thickness overlie silt- or clay-size mill tailings and(or) mixed fine-grained mill tailings and pond sediment. Site 3-390 does not contain identifiable mill tailings. Pond-fill sediment overlie the Mazama ash and coarse-grained alluvium at sites UFMC 3-200, 3-300, and 250-200.

The depositional history of the mill tailings here is complex. Mill tailings from Area A (fig. 3), upstream from the main mill tailings area, were transported by Frohner Meadows Creek to this area and were deposited in a natural pond behind a beaver dam. A second source of mill tailings, based on observations in cores UFMC 1 and 3-0, appears to have been fine-grained mill tailings, probably from the Nellie Grant mill, that were released into Nellie Grant Creek and entered the pond to form a delta. These also were apparently dispersed into the center of the meadow. Later, coarse-grained mill tailings, probably also from the Nellie Grant mill, were released and covered the earlier fine-grained mill tailings and then were partially removed by erosion and dispersed into the center of the meadow.

Two sites (4-0 and 4-100) that lie immediately below the main mill tailings impoundment (fig. 11) were sampled to determine the extent of which mill tailings have been transported downstream into the meadow/pond system. At site 4-0, an 11-cm-thick clay- and vegetation-rich layer overlies clay-rich pond deposits, which are a mixture of silt- and clay-sized pond-fill deposits and transported clay- or silt-size mill tailings that are 14-cm thick. Fine-grained alluvial sand, older pond deposits, and Mazama ash underlie these pond-fill deposits and transported mill tailings. Enriched material, found only at site 4-0, is greater than 62-cm thick. The stratigraphy in 4-100 is similar to that in 4-0 except that Mazama ash is not present.

The WAC concentrations calculated for cores in Area B are shown in figure 13. Mill tailings and underlying fine-grained, pond-fill deposits in all cores from 3-0 to 3-300 inclusively and 250-75 and 250-200 are highly enriched in cadmium. Zinc is highly enriched at all sites and highly variable between sites; overall the WAC's are about 2 times higher than those of Area A (fig. 10). The degree of enrichment of arsenic and lead is 50 to 100 percent lower than those in Area A, although arsenic and lead are well above geochemical threshold metal concentrations for cores. Copper WAC values are higher relative to those in Area A but show slight enrichments relative to threshold concentrations. WAC values in the silt- and clay-rich deposits in core 4-0 are lower than samples from the mill tailings impoundment immediately upstream for all metals except cadmium. Near-surface samples from core 4-100 were not chemically analyzed; the fine-grained sand that underlies the upper pond sequence shows no significant metal enrichments. The WAC for cadmium and zinc in UFMC 1 is similar to other cores in the Area B, however, the arsenic and lead WAC concentrations are much lower. The area in which this core was taken is in an artesian outflow zone from Nellie Grant Creek, and the enrichment of zinc and cadmium relative to lead and arsenic may be due to metals from a metal contaminated ground-water plume. This interpretation is supported by the high concentrations of zinc and cadmium that are found in surface water in Nellie Grant Creek and in ground water in monitoring well MW-1 (fig. 22, table 9).

Figure 8. Map of the upper mill tailings area (Area A, fig. 3), upper Frohner Meadows, showing thickness of metal-enriched material and depth of the bottom of metal-enriched interval.

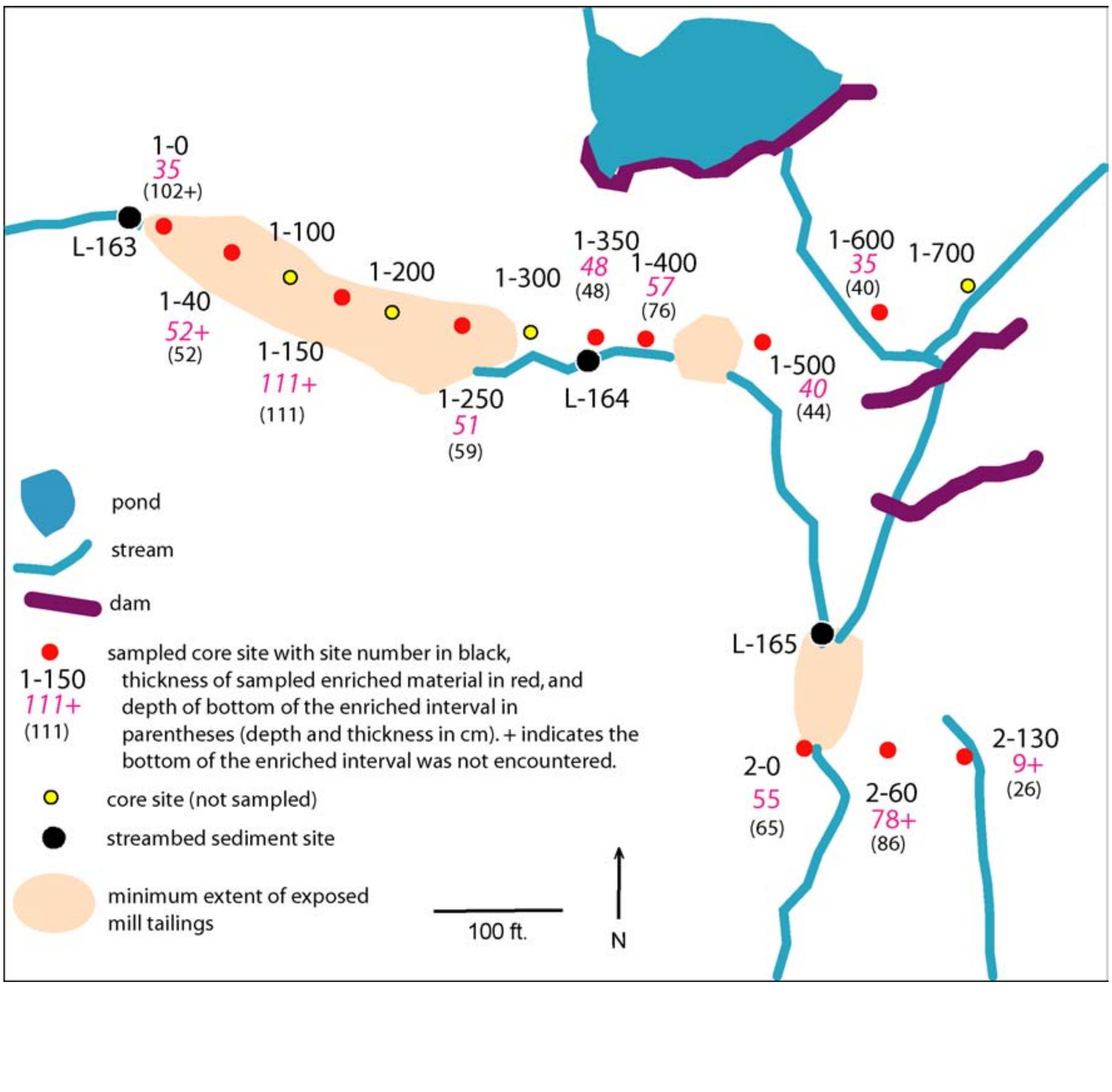


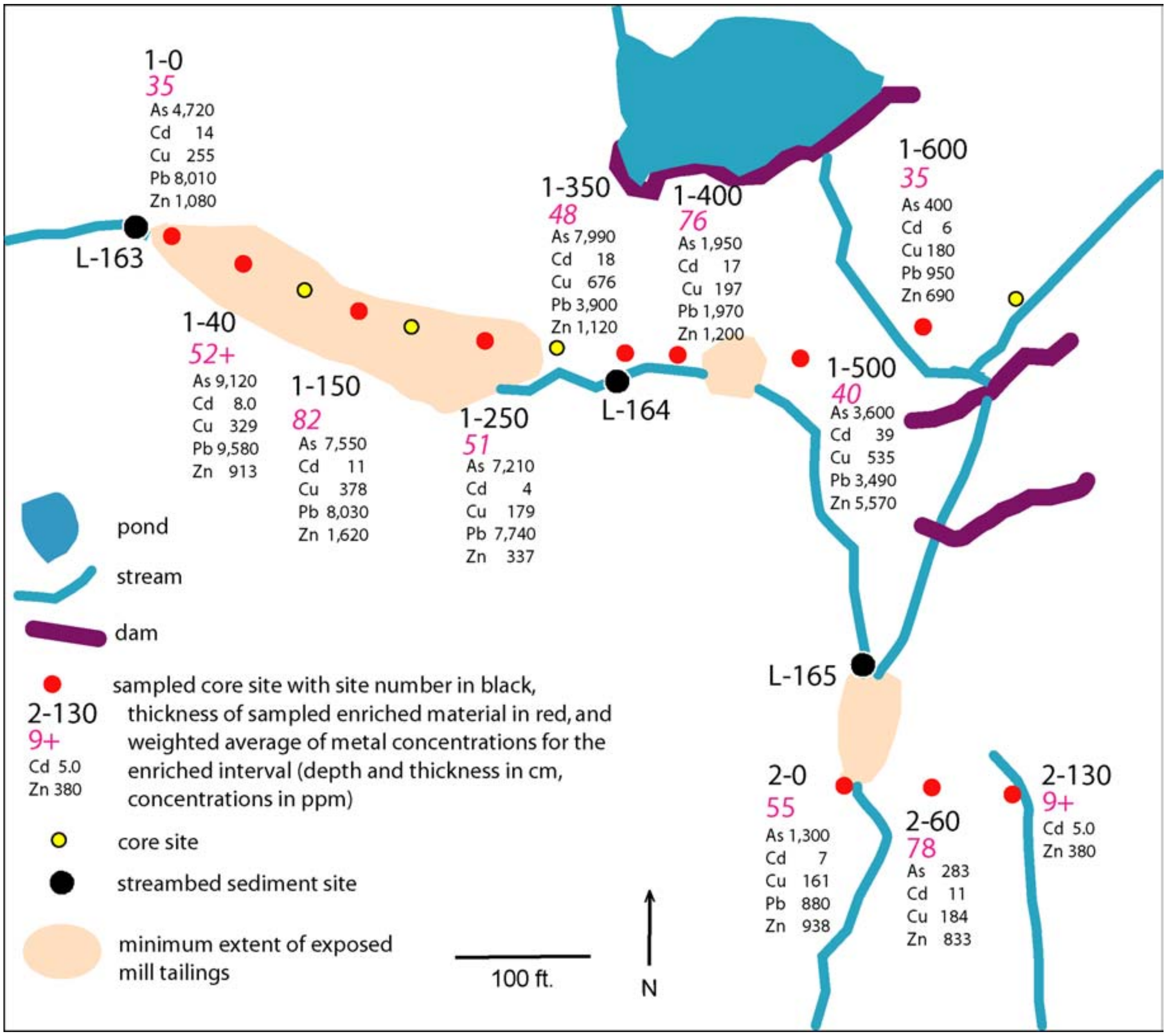
Figure 9. Cross section of mill-tailings debris fan along Frohner Meadows Creek in Area A in upper Frohner Meadows (fig 11). Stratigraphic units are labeled.

Lower Frohner Meadow

Lower Frohner Meadow (Area C, fig. 3) contains several water-filled abandoned beaver ponds and many dry ponds with breached dams (fig. 14). In most of the breached beaver ponds, streams are eroding the highly organic and clay-rich pond-fill deposits and forming incised stream channels. The ponds (both wet and dry) are separated by relatively dry meadowlands in the upper part of the meadow system and by wetlands in the lower part, near the meadow outlet. In the uppermost pond, which is water filled, a small delta of mill tailings was deposited in its southwest corner from the most recent mining activity at the Nellie Grant (verbal communication, Jack Yates, Montana Department of Environmental Quality).

The minimum extent of the mill-tailings delta, based on a visual estimate, is shown in figure 14. The delta was characterized with one 125-cm core at site LFMC 1. Enriched material that consists of fine sand-size mill tailings grades downward into clay-rich pond deposits is approximately 40-cm thick. Fine-grained pyrite is abundant; partially oxidized pyrite is present to about 30-cm depth. The mill tailings are water saturated and form a marshy area near the high-water level of the pond.

Figure 10. Map of the upper mill tailings area (Area A, fig. 9) upper Frohner Meadow showing thickness of enriched material and thickness-weighted averages of metal concentrations for the enriched interval.



Sample line 5 is about 300 ft downstream from the mill-tailings delta in a relatively flat dry meadow. Five cores, ranging in depth from 73 to 137 cm, were taken at 100 ft intervals along line 5. Pond-fill deposits 35- to 96-cm thick overlie Mazama ash, periglacial fluvial deposits and(or) moraine deposits in all cores.

Along line 6, fine-grained pond-fill deposits in a breached beaver pond were sampled. The pond-fill deposits range from 19- to 61-cm thick and consist of fine-grained, highly organic clay and silt with abundant woody debris. These deposits overlie medium- to fine-grained alluvial deposits and periglacial fluvial sediment.

Cores LFMC 1 and 6-0 contain the highest metal WAC concentrations for this Area C (fig. 15). Samples of mill tailings from LFMC 1 show WAC values similar to core 3-0 in Area B (fig. 13), the source of which also is probably the Nellie Grant mine. The enriched material consists of fine-grained mill tailings; some underlying clay-rich pond-fill deposits have the characteristic high levels of enrichment of cadmium and zinc and relative to arsenic and lead found in Nellie Grant mine waste and mill tailings. Core 6-0 has similar WAC values of arsenic, cadmium, and zinc compared to LFMC 1 but has a much higher lead WAC. The source of this lead enrichment may be clastic grains of lead-rich minerals transported by Frohner Meadows from mill tailings in Upper Frohner Meadows, where mill tailings have higher degrees of lead enrichment than those in Lower Frohner Meadows. The most enriched material found in the upper part of the fine-grained pond-fill deposits in the core 6-0 consists of organic material only; fine-grained alluvium in the lower portion (below 31 cm) was not analyzed.

Figure 11. Map of the main mill tailings area (Area B in fig. 3) in upper Frohner Meadow showing thickness of enriched material and depth of the bottom of enriched interval.

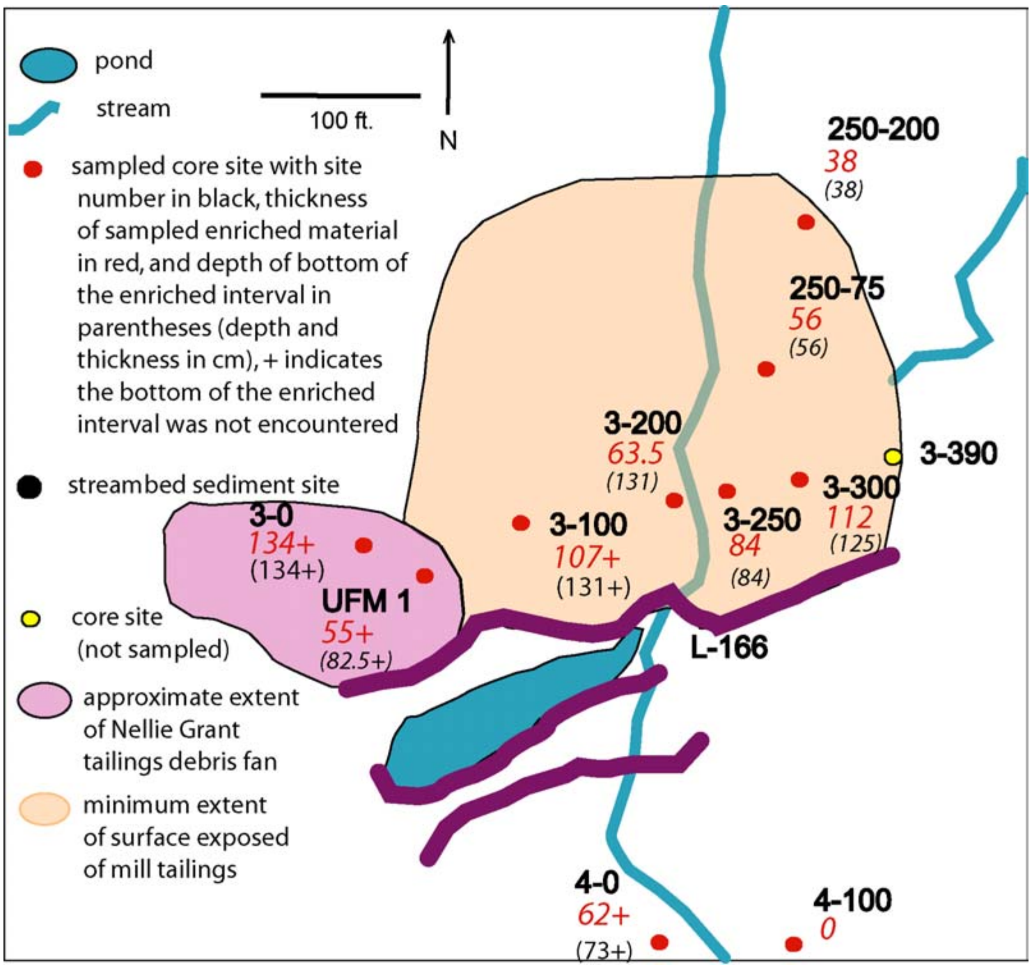
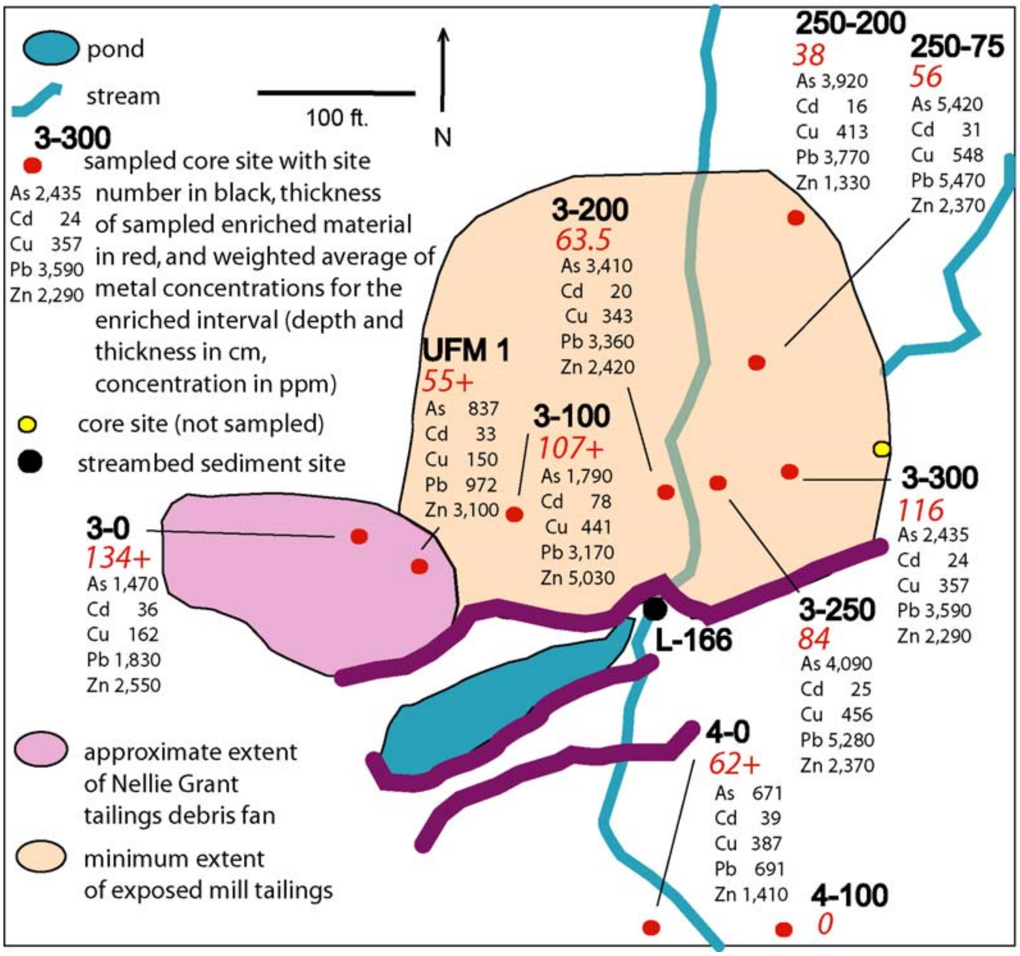


Figure 12. Mill tailings exposed along Frohner Meadows Creek in Area B of upper Frohner Meadows (fig. 3) in the main mill tailings impoundment. Coarse quartz chips form a lag deposit overlying fine-grained oxidized fine mill tailings.

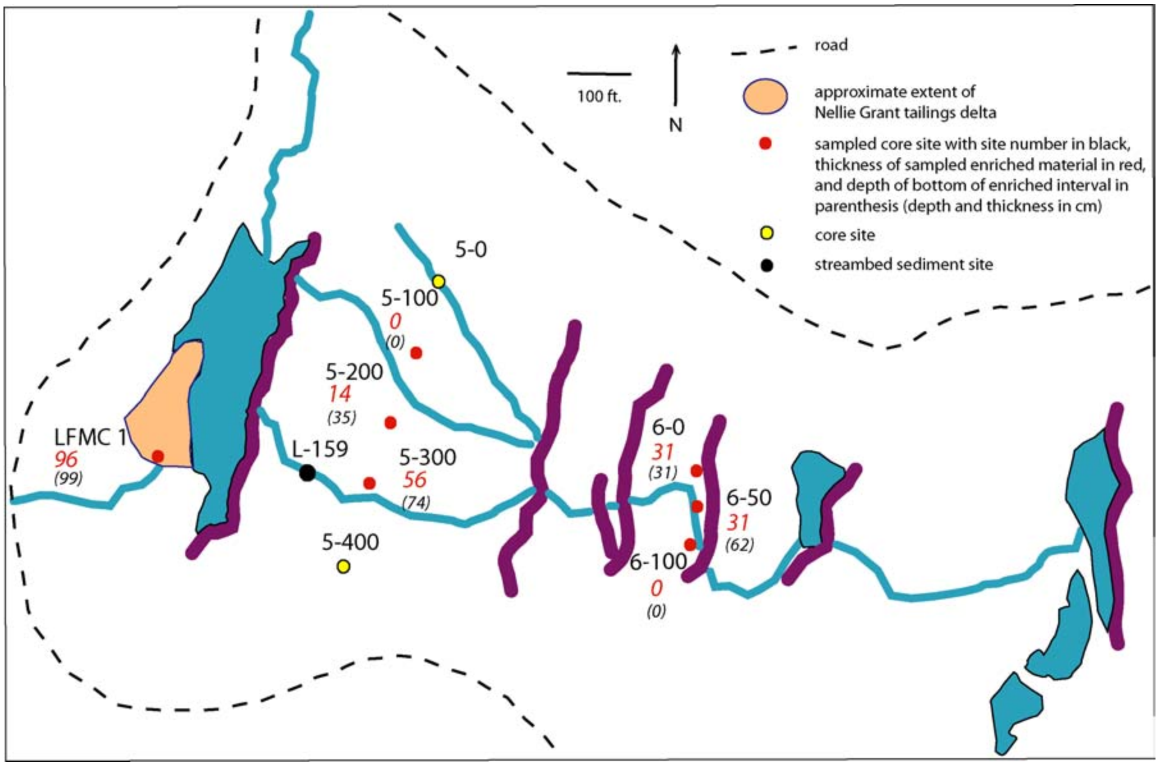
Sites 5-200 and 5-300 show moderate concentrations of the ore-related metals in fine-grained pond-fill with the greatest thickness of enriched material at site 5-300. The horizontal and vertical extent of contaminated material along line 5 was not adequately defined by sampling. Samples from 5-0 and 5-400 were not analyzed, and at site 5-100, only alluvium (below 113 cm) lying below pond-fill deposits was analyzed; and it contained metals below threshold concentrations (table 2).

Figure 13. Map of the main mill tailings area, upper Frohner Meadows, showing thickness of enriched material and thickness-weighted averages of metal concentrations for the enriched interval (Area B in fig 10.).



In all core samples in Lower Frohner Meadows, the metal-enriched material is confined to the fine-grained upper part of the pond-fill deposits. In some cases, the lower part of the fine-grained pond-fill deposits were uncontaminated. In all cases, the coarser grained alluvium underlying the fine-grained pond deposits is uncontaminated suggesting that deposition of metal from ground water is not an important factor in metal accumulation in this area. Ore-related metals were not enriched to a significant degree in the older buried alluvial material.

Figure 14. Map of Lower Frohner Meadows (Area C in fig. 3) showing thickness of enriched material and depth of the bottom of enriched interval.

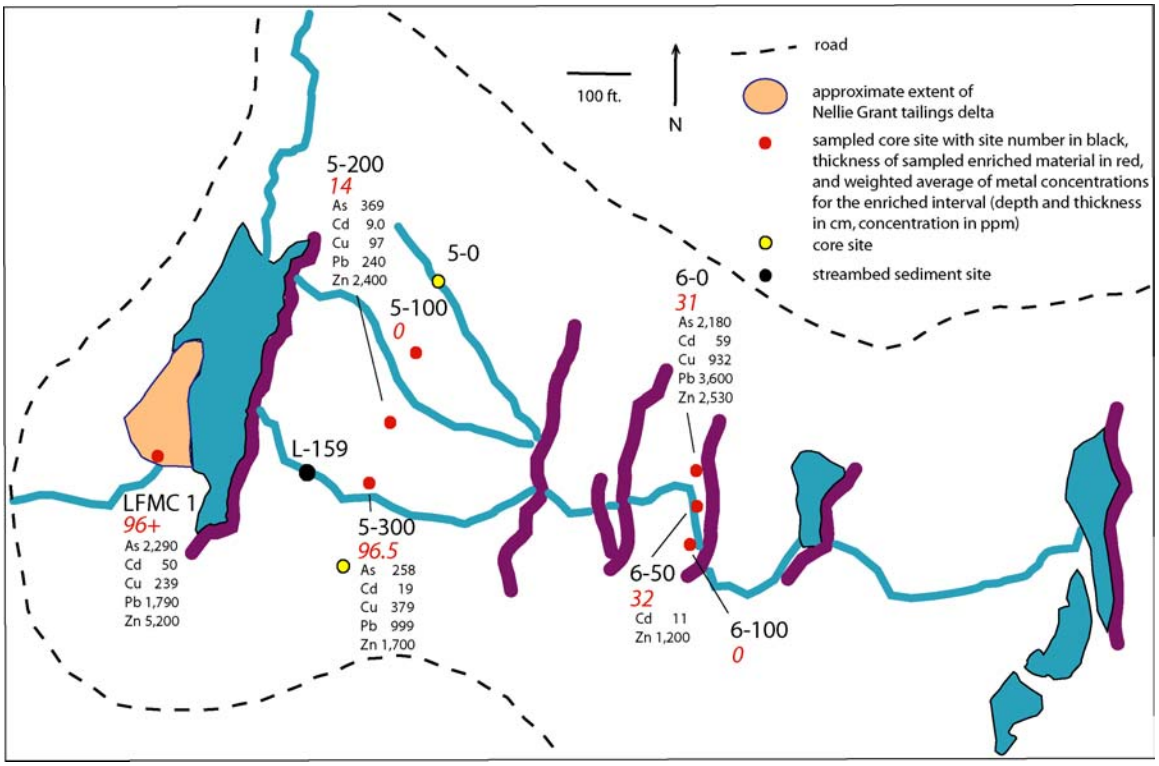


Upper Lump Gulch

Frohner Meadows Creek discharges into upper Lump Gulch in the southeastern part of the study area. A small meadow has formed in a sediment-filled reservoir in upper Lump Gulch about 700 ft below the Frohner Meadow outlet (fig. 3). A water-diversion structure here is the source of water for Park Lake, which lies about 1 mile to the northeast. Streambed sediment and water samples taken during 2000 during a watershed-characterization study identified ore-related metal enrichments at the outlet of Frohner Meadows (Klein and others, 2001). These metal concentrations are reduced substantially through the stream reach below this reservoir in upper Lump Gulch.

Three core samples (ULGFR 1, 2, and 3) that ranged from 132 to 190 cm in depth were taken to determine the mechanism that reduces metal concentrations in water and streambed sediment below the outlet of Frohner Meadows. The upper 20 cm of core ULGFR 1 is dark red silt that appears to be oxidized fine-grained transported mill tailings (Klein and others, 2003b). The lower parts of the all cores are interbedded thick pond-fill deposits and fine-grained alluvium that are up to 157-cm thick. In cores ULGFR 1 and 3, which are deeper than ULGFR 2, interbedded pond fill and fine-grained alluvium overlie very coarse, poorly sorted alluvium that probably are periglacial in origin.

Figure 15. Map of Lower Frohner Meadows (Area C in fig. 3) showing thickness of enriched material and thickness-weighted averages of metal concentrations for the enriched interval.



Because ore-related metal enrichment in these cores mostly is low level and vertically discontinuous, WAC concentrations were not calculated. In ULGFR 1, the upper 20 cm, interpreted to be fine-grained fluvial-mill tailings, is highly enriched in cadmium and zinc and moderately enriched in arsenic and lead relative to their respective threshold concentrations. Near the bottom of this core, between 91- to 152-cm low-level cadmium and zinc enrichments occur in medium- and coarse-grained alluvium that have abundant manganese oxyhydroxide grain coatings. Arsenic is slightly enriched in this interval at about 2 times the premining threshold level. Clay-rich, highly organic pond-fill deposits enclose this coarse grained alluvium.

Arsenic, cadmium, and zinc are slightly enriched relative to the local geochemical threshold concentration (table 4) in medium-grained alluvium near the surface in core ULGFR 2, and cadmium and zinc also show slight enrichment in interbedded fine sand and clay that lie beneath clay-rich pond fill near the bottom of the core. Coarse-grained alluvium in the upper part of core ULGFR 3 shows slight enrichment of zinc and cadmium, whereas the bottom 30 cm contains slight enrichments of arsenic and lead in coarse-grained alluvium.

Cadmium and zinc enrichments in buried permeable, medium- and coarse-grained alluvium in cores ULGFR 1 and 2 suggest that these metals may be accumulating in the subsurface from metal-enriched ground water. The two deepest samples in ULGFR 1 and the deepest sample in ULGFR 2 lie below clay layers that may restrict the ground-water flow into the underlying more permeable coarse-grained alluvial layers. The most likely metal source is the highly contaminated surface water that leaves Frohner Meadows near site L-3b, immediately upstream from this reservoir site. The enrichment of all ore-related metals in the uppermost samples of these two cores may be due to clastic transport of arsenic and lead in mineral grains and solution transport of cadmium and zinc in the most recent alluvial material filling the reservoir. Clastic transport of zinc and cadmium-enriched iron and manganese oxyhydroxides grain coatings from upstream sources may also contribute to their enrichment in these shallow deposits.

Site ULGFR 3 lies along a tributary of the south fork of upper Lump Gulch Creek that drains Frohner Meadows through site L-3a. The near surface low-level cadmium and zinc enrichment in this core probably is due to the cadmium- and zinc-enriched surface water that leaves Frohner Meadows upstream from L-3a. The two deepest samples in ULGFR 3 contain low-level enrichments of arsenic and lead. Arsenic may be transported in ground water under reducing conditions as seen in some ground-water monitoring wells in Upper Frohner Meadow but lead with a very low solubility in water under all natural conditions only can be transported in significant concentrations as clastic material. Therefore, these enrichments probably are due to the clastic transport of arsenic- and lead-bearing minerals early in the history of this reservoir that predates the pond-filling sedimentation that occurred prior to the construction of the impoundment and diversion structure.

Panama Mine Meadows

A large, and abandoned sediment-filled reservoir that lies about 1 mile southwest of lower Frohner Meadow was sampled to determine the origin of the fill material. The reservoir consists of a series of dry and water-filled beaver ponds and intervening meadows that have developed behind a breached diversion dam (fig. 3). Three cores (PMC 1, 2, and 3), ranging in depth from 58 to 80 cm, show that the deposits that fill the reservoir consist of interbedded pond-fill deposits and medium- to coarse-alluvial sand and gravel consisting largely of granite pebbles (Klein and others, 2003, Appendix 1). These coarse clastic sediment deposits are locally derived material from the surrounding granitic rocks of the Boulder Batholith.

Slight arsenic and lead enrichment occurs in one clay-rich pond-fill interval in core PMC 3 (Klein and others, 2003b). The source and extent of the slight arsenic and lead enrichments are unknown. Background metal concentrations in water and streambed sediment at site L-1 (Klein and others, 2001) show that the slight enrichment of concentrations relative to premining concentrations of lead and arsenic are not contributed to the meadow deposits through the active stream system. Samples from PMC 1 showed no unusual metal accumulations.

Comparison of the thickness-weighted average ore-related metal concentrations in core samples

Weighted averages for the five ore-related metals from all enriched intervals in cores in each of the three areas (A, B, and C in fig. 3) were calculated as a way of comparing the bulk chemistry among areas containing enriched material. The results (table 3) allow comparison of the bulk-metal concentrations of the material that is present in different parts of the meadow system in terms of their potential for contributing metals to ground and surface water and streambed sediment and as an estimate of the bulk concentrations in contaminated material, which may be useful during possible remediation efforts.

Cores from Area A contain the highest bulk concentrations of arsenic and lead, whereas cores from Areas B and C are highest in cadmium and zinc which is similar to the relations observed in the bulk-surface samples of mine and mill tailings from these same areas. These average concentrations from cores in Areas A, B, and C greatly exceed the geochemical threshold concentrations for each metal (table 2) and illustrate the high degree of metal enrichment in these areas. The weighted averages of metal concentrations for enriched material in the filled reservoir in upper Lump Gulch are near or below core clastic-material, geochemical-threshold concentrations for arsenic, copper, and lead and at about the 2x the threshold concentrations for cadmium and zinc.

Table 3. Weighted average concentration of contaminated material encountered in core samples by area. All concentrations are in ppm.

Area	Arsenic	Cadmium	Copper	Lead	Zinc
A	3,520	12	268	3,520	1,190
B	1,980	36	293	2,650	2,860
C	277	11	189	595	863
Lower Frohner Meadow mill tailings (LFMC 1)	2,290	50	239	1,790	5,200
Upper Lump Gulch filled reservoir	109	9	66	156	648

Ore-related Metals in Streambed Sediment

Streambed-sediment sampling is used to locate stream reaches that are enriched in metals due to natural or human causes. Concentrations of metals in streambed sediment present a time-integrated view of the chemical input from erosion of underlying bedrock and glacial debris upstream from the sample site and input from natural or cultural point sources, for example outcropping mineral deposits or abandoned or active mines and mills. Ore-related trace metals (arsenic, cadmium, copper, lead, and zinc) typically are enriched downstream from natural outcroppings of base- and precious-metal deposits and below mine and mill sites such as those in the Frohner Meadows area. Ore-related metals accumulate in streambed sediment either as detrital grains of the original ore minerals or host rock or as secondary minerals formed during weathering of ore minerals. The bulk of the secondary minerals is composed of colloidal iron and manganese oxyhydroxides, which generally accumulate as coatings on sediment grains. These coatings are relatively unstable; they are easily eroded and transported during periods of increased stream discharge, dissolved by changes in oxidation-potential of stream water, and may be leached from grain coatings by changes in the pH of stream water. Other physical variables, such as stream velocity, changes in stream gradient, and shallow ground-water inputs, also can affect the amount of metal in streambed sediment.

The biogeochemical effects of high-metal concentrations in streambed sediment on the ecosystem and surface-water chemistry are complex. In terms of ecosystem effects, metals in streambed sediment impact the accumulation of metals in benthic fauna, which feed on and live in streambed sediment (MacDonald and others, 2000). Benthic fauna is a major food source for many freshwater fish, and metals accumulated from streambed sediment by benthic fauna may be transferred to fish (Farag and others, in press). The effects of metals in streambed sediment on water chemistry are more complex. The silicate and oxide mineral grains that make up most of the streambed sediment are relatively resistant to weathering and release only small amounts of metals over a long time span during weathering (Church and others, 1993). Thus, high concentrations of those metals in silicate and oxide grains likely do not have a great effect on water chemistry. However, metals found in iron and manganese oxyhydroxide grain coatings can have a marked effect on water chemistry because relatively large-scale releases of metals into the water column may be induced by changes in water chemistry, such as oxidation potential and pH, or flow conditions over a short time period (Horowitz and others, 1991).

Regional Background Metal Concentrations in Streambed Sediment

Regional streambed-sediment background-metal concentrations were determined in Klein and others (2001) for the upper Prickly Pear Creek watershed (fig. 1). Samples sites for the background determinations were chosen from streams that drain areas with little or no mining history and that have typical unmineralized-granitic bedrock found in much of the watershed. Background concentrations for arsenic, cadmium, copper, lead, and zinc are in table 4. These background concentrations (total digestion) are much higher than their respective mean-crustal abundances in granitic rocks. These elevated background concentrations, in part, may relate to enrichments related to regional-scale hydrothermal alteration that resulted in the formation of the many base and precious-metal deposits in the heavily mineralized northern part of the Boulder batholith. These regional-background concentrations for the upper Prickly Pear Creek watershed were used to evaluate the degree of enrichments of the ore-related metals in streambed sediment samples from Frohner Meadows.

Streambed Sediment Screening Concentrations

The effect of metals in streambed sediment on the health of aquatic organisms is one measure of the biological impact of contamination from metals in a stream reach. Attempts have been made to establish the minimum concentrations of various metals in streambed sediment that affect the health of aquatic organisms. But the mechanisms of metal uptake and the effects of metals on organism health are poorly understood, and no standard has yet been adopted by any major environmental agency. The consensus-based probable effect concentrations (CBPEC) were developed using an approach where the protective concentrations of metals were determined by a consensus of multiple methodologies (MacDonald and others, 2000). A CBPEC identifies the contaminant concentration above which harmful effects on sediment-dwelling organisms frequently occur. CBPEC values were derived using the geometric-mean concentration of selected published effects-based sediment-quality guidelines. The chemical analyses of the sediment used to establish the CBPEC used total analyses. These concentrations then were evaluated for reliability by using paired sediment chemistry and toxicity data. The CBPEC (MacDonald and others, 2000) are used in this report to relate metal concentrations in the streambed sediment in Frohner Meadows to concentrations of metals that may produce toxic effects on aquatic organisms.

Table 4. Median trace metal concentrations of regional background streambed sediment samples in the upper Prickly Pear Creek watershed (PPC) (Klein and others, 2001, table 2) and median concentrations of streambed sediments in the study area (FM).

[Mean crustal abundances for granitic rocks are "total" analyses and are from Rose and others (1979). All concentrations in ppm; standard deviations in parentheses. "n" is the number of samples]

	Dilute-acid partial digestion			Total digestion			
metal	PPC	n (PPC)	FM	PPC	n (FM)	FM	Mean crustal abundance granitic rocks
Arsenic	6.6 (4.8)	6	720 (711)	14 (5)	15	950 (1,196)	2
Cadmium	1 (0.3)	6	25 (21)	4 (1)	16	33 (27)	0.1
Copper	15 (8)	6	115 (59)	42 (24)	33	170 (92)	12
Lead	12 (7)	6	770 (1,110)	25 (9)	30	1,250 (1,620)	18
Zinc	80 (33)	6	2,000 (1,420)	96 (31)	15	2,500 (1,840)	51

Table 5. Summary of consensus-based probable-effects concentrations (CBPEC) for streambed sediment (MacDonald and others, 2000).

Element	*CBPEC (ppm)*
Arsenic	33
Cadmium	4.98
Copper	149
Lead	128
Zinc	459

Investigation of Streambed Sediment

A comparison of the results of the total- and dilute-acid partial digestion of streambed sediment for ore-related metals (Klein and others, 2003b) in the Frohner Meadows with the median upper Prickly Pear Creek watershed background concentrations (table 4) illustrates the highly enriched nature of the sediment in Frohner Meadows Creek. Metal concentrations at all of the streambed-sediment sites in stream reaches below the mine and mill areas are 8 to 100 times greater than the watershed median-background concentrations for arsenic, cadmium, lead, and zinc for dilute-acid partial and total digestions. A similar comparison of median-copper concentrations shows that the study area is 7 times higher than the median-background concentrations for the dilute-acid partial digestion and 4 times higher for the total digestion. A comparison of the same data to mean-crustal abundance for granitic rocks shows similar or greater enrichments (table 4).

These data illustrate that Frohner Meadow Creek is enriched in ore-related metals relative to mean-crustal abundance and to regional-background concentrations.

Comparison of the same data (table 4) with CBPEC concentrations (table 5) shows that in Frohner Meadows Creek median concentrations (total and dilute-acid partial digestions) exceed the CBPEC concentrations in arsenic, cadmium, lead, and zinc by 5 to nearly 30 times. This comparison indicates that concentrations of these ore-related metals in streambed sediment in Frohner Meadow Creek downstream from the mine and mill areas far exceed any streambed-sediment metric for aquatic health. Median-copper concentrations in Frohner Meadows Creek are at a similar level to the CBPEC, which suggest that copper concentrations are less of a threat to aquatic health than the other ore-related metals.

Downstream plots of ore-related metal concentrations

The identification of ore-related metal sources and interpretation of downstream changes in metal concentrations are aided by downstream-concentration plots, where the measured concentration at a site and a constant rate of change in concentration between adjacent sites are illustrated with a connecting line. These plots provide a graphical tool by which changes in metal concentration can be evaluated in terms of sources and chemical and physical processes. Dilute-acid, partial-digestion metal concentrations were used to construct the plots because the metals liberated by this dilute-acid digestion are more readily available to aquatic organisms and stream water. The chemical analyses of samples using this digestion are given in Klein and others (2003b, table 8).

Sites L-152-155, L-4, and L-4a are outside the study area and lie downstream, in that order, from site L-156 in upper Lump Gulch but were included in the downstream plots to illustrate the impact of Frohner Meadows on streambed sediment downstream in upper Lump Gulch. Data for those sites are summarized in Klein and others (2003a).

Changes in streambed-sediment, dilute-acid, partial-digestion concentrations for arsenic, cadmium, copper, lead, and zinc as a function of downstream distance are shown in figures 16–21. In each figure, the element concentration is on the vertical axis, and the downstream distance is on the horizontal axis. The downstream distances are from an arbitrary starting point; the left of the figure is upstream, and the right is downstream. In each plot, the green solid line connects metal concentration data for sites along Frohner Meadows Creek, beginning above site L-2 and continuing downstream through upper and lower Frohner Meadows to site L-3b. Lump Gulch begins in a small, sediment-filled reservoir (at site L-l56) at the junction of the tributary that drains the Panama Mine Meadows (fig. 3). Below this reservoir, the stream in Lump Gulch flows from site L-156 to L-4 and beyond. The solid yellow line connects metal concentration data for streambed sediment from the Panama Mine tributary. The dashed green line connects lower Frohner Meadows with the Panama Mine Meadow tributary. Water from lower Frohner Meadows flows from the meadow primarily in a channel at the eastern end at site L-3b, as well as through a second channel that emerges from the meadow's southern edge and connects with the Panama Mine tributary. The Panama Mine tributary mostly is unaffected by contaminated sediment and appears to dilute the sediment ore-related metal concentrations in Frohner Meadows Creek when they converge to become Lump Gulch downstream from site L-156.

Arsenic

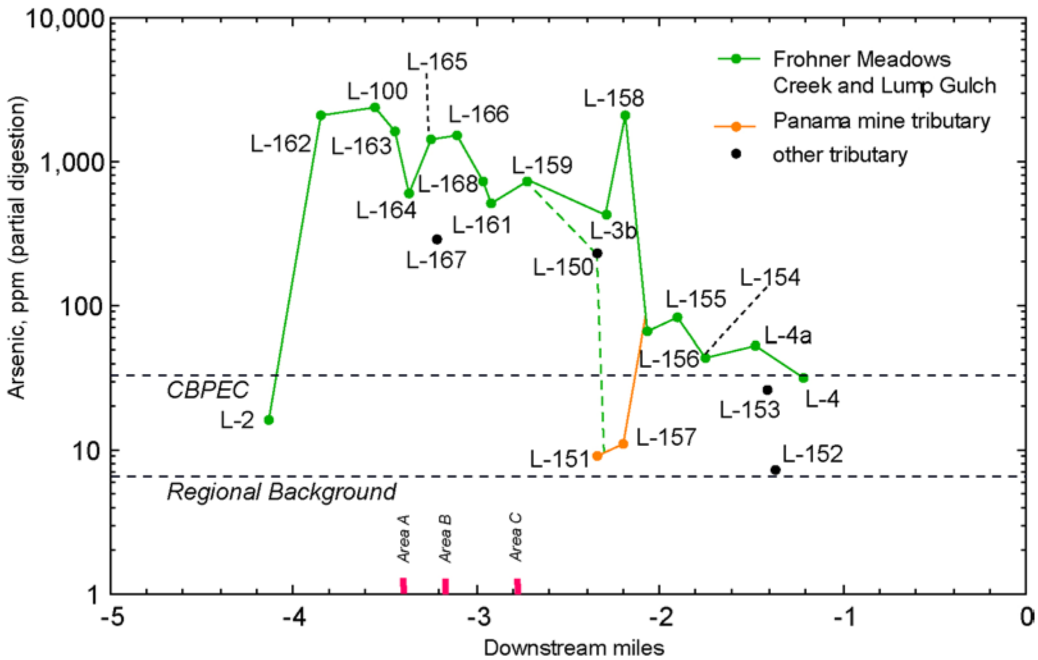
The dilute-acid, partial-digestion arsenic concentration above the Frohner mine (site L-2, fig. 16; 10 ppm) was near the background concentration of 6.6 ppm (table 4). The next site, L-162, is just below the historical Frohner mill site, where a large volume of crushed-ore material is present at surface and in an old ore bin. Erosion has distributed the crushed ore down the relatively steep slope into Frohner Meadow Creek. The arsenic concentration in streambed sediment here was over 2,000 ppm. Downstream through upper and lower Frohner Meadows, arsenic concentrations remained variably high relative to the upstream samples, although a general trend toward lower concentrations downstream through sites L-165 through L-161 probably was caused by dilution with additional sediment with a lower arsenic concentration. The small increase in arsenic concentration in the upstream site (L-159) in lower Frohner Meadow probably was due to the addition of arsenic-enriched material from the mill tailings situated at the western end of the lower meadow near bulk sample site LFM-1.

At site L-158, the concentration of arsenic dramatically increases. This increase in arsenic concentration is accompanied by a large increase in the manganese and iron concentrations, which may be the result of their deposition during oxidation of iron and manganese from spring water from Frohner Meadows as the water enters the stream between sites L-3b and L-158. The coincidental increase in arsenic concentration may be linked to oxidation of arsenic-rich ground water from lower Frohner Meadow. However, the extreme lead concentration at this site (see below) argues against the transport in solution and suggests the high concentrations are due to detrital processes. The arsenic concentration decreases substantially between site L-158, just above the Upper Lump Gulch sediment filled reservoir, and the reservoir outlet (site L-156). Based on field observations such as flood-plain width, it is likely that the Panama mine tributary contributes far more detrital material to the filled reservoir than Frohner Meadows Creek. Field observation above site L-3b suggests that little coarse detrital material leaves lower Frohner Meadow because of its numerous dams, ponds, and wetlands. Very low arsenic concentrations at sites L-151 and L-157 confirm that streambed sediment from the Panama Mine tributary likely is not contaminated. The tie line between L-157 and L-156 (fig. 16) illustrates that streambed sediment with low arsenic concentration from the Panama Mine tributary dilutes the arsenic concentration from typical Frohner Meadows Creek concentrations below the junction of these streams.

Cadmium

The cadmium concentration at site L-2, as with arsenic, is quite low at the median for background sites (figure 17; table 4). The concentration rises to 16 ppm below the Frohner mill site (L-162). Tailings from the mill site are not particularly high in cadmium with samples at sites FMB-1 and 2 containing 9 and 4 ppm, respectively (table 6 of Klein and others (2003b)), so it probably contributes little cadmium to the streambed sediment. However, the cadmium concentration at site L-100 increases substantially to 46 ppm. Cadmium is quite soluble and mobile at the near-neutral pH of the stream waters found throughout Frohner Meadows and as a result can be transported in solution, as well as in detrital mineral grains; it also can be removed from solution by sorption on iron or manganese oxyhydroxides (Horowitz and others, 1991). The correlations in streambed-sediment, dilute-acid, partial-digestion iron and cadmium concentrations and between

Figure 16. Downstream plot for arsenic concentration (partial digestion) in streambed sediment of Frohner Meadow Creek and Lump Gulch.



dilute-acid, partial-digestion manganese and cadmium concentrations in this study are strong. The R^2 value for iron and cadmium is 0.85, and the R^2 value for manganese and cadmium is 0.71. The dilute-acid, partial-digestion concentrations of iron and manganese at L-100 are high–23,000 and 16,000 ppm, respectively (Klein and others, 2003b, table 8). Thus, high iron and manganese oxyhydroxide content of streambed sediment at that site may scavenge cadmium from the dissolved phase and cause concentrations that are much higher than at L-162. Scavenging of cadmium by iron and manganese oxyhydroxides from contaminated surface water probably is responsible for the high streambed-sediment concentrations in many sites in the study area.

Streambed-sediment cadmium concentrations decrease downstream from site L-162 to site L-164 probably resulting from dilution by nonenriched streambed sediment. Then, concentrations increase from site L-165 in upper Frohner Meadow downstream through the eastern end of lower Frohner meadow site L-3b.

Cadmium also is transported out the south outlet of lower Frohner Meadows, as seen in the high concentration (40 ppm) at site L-150. Streambed sediment from the Panama meadow tributary dilutes the south outlet sediment as seen at site L-157 where the concentration drops to 3 ppm. However, the dilution at site L-156 is not as marked as that for arsenic, probably because continued solution transport of cadmium out of Frohner meadows results in cadmium deposition onto iron and manganese oxyhydroxide grain coatings during low-flow conditions when clastic transport is minimal. This process is relatively independent of clastic sediment dilution effects.

The downstream plot of dilute-acid partial-digestion concentrations of iron and manganese (fig. 18) illustrates that the overall patterns of both metals are similar to that of cadmium. This similarity supports the hypothesis that cadmium is accumulating from streamwater as the result of sorption on iron and manganese oxyhydroxide grain coatings. The highest concentrations of iron and manganese are at site L-158. Most ore-related metal concentrations below this site decrease dramatically suggesting that some of the transported metals (cadmium and zinc) may be removed from the streamwater by sorption on manganese and iron grain coatings near this site. Similar effects also may occur in the lower part of lower Frohner Meadow above site L-3b.

Large seasonal variations of dissolved arsenic, cadmium, and zinc in streamwater were observed at site L-3b. In addition, there were large variations in the concentrations of these constituents in the streambed sediments collected in October 2000 and July 2001. These large variations may be related to solubility reactions between surface water and iron and manganese oxyhydroxide grain coatings of streambed sediments and surficial deposits in this marshy area in response to temporal changes in water chemistry. Alternatively, some of the variation may be related to sample variation. At site L-3b, at the outlet of lower Frohner Meadow, and at site L-100, we collected samples both in October 2000 and July 2001. In both samples, sediment concentrations of all the ore-related trace metals were lower in 2001 than in 2000. However, the major elements–aluminum, calcium, potassium, and sodium–were all higher in 2001, indicating that the sample collected had a higher proportion of lithic material (decomposed, plutonic rock-forming minerals), which would dilute the concentration of ore-related trace metals. Importantly, the iron and manganese concentrations in the samples from 2001 were lower (58 percent and 33 percent in L-3b, respectively). The lower concentrations of these scavenging elements had an effect on the concentrations of the other elements. Whether the lower concentrations of iron and manganese were due to temporal differences in water chemistry or heterogeneity of material at these sites is not known.

Figure 17. Downstream plot for cadmium concentration (dilute-acid partial digestion) in streambed sediment of Frohner Meadows Creek and Lump Gulch.

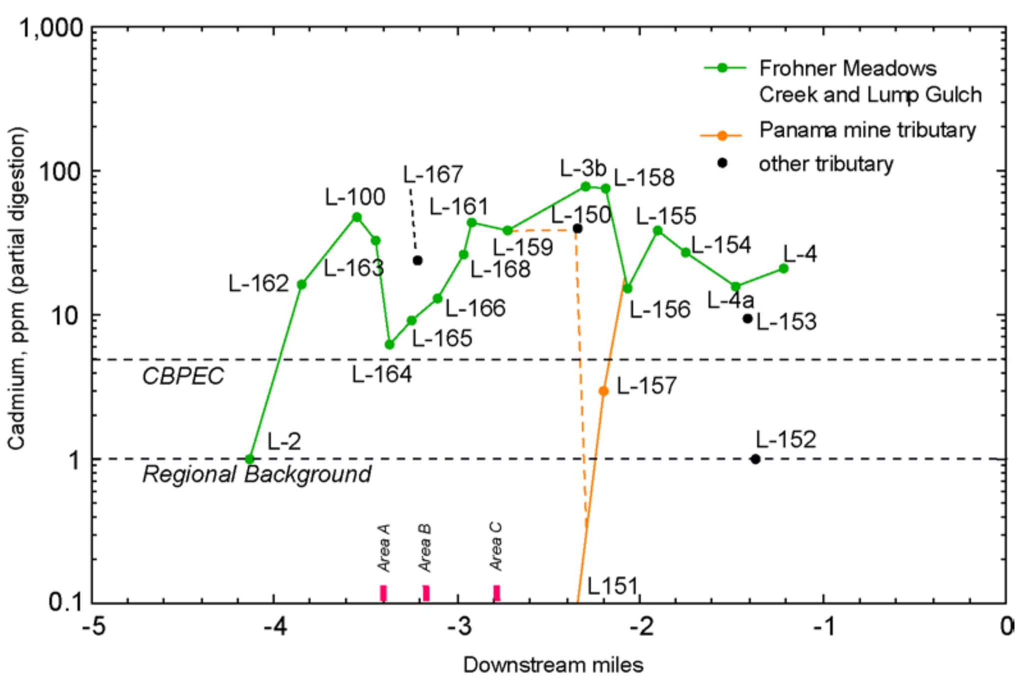
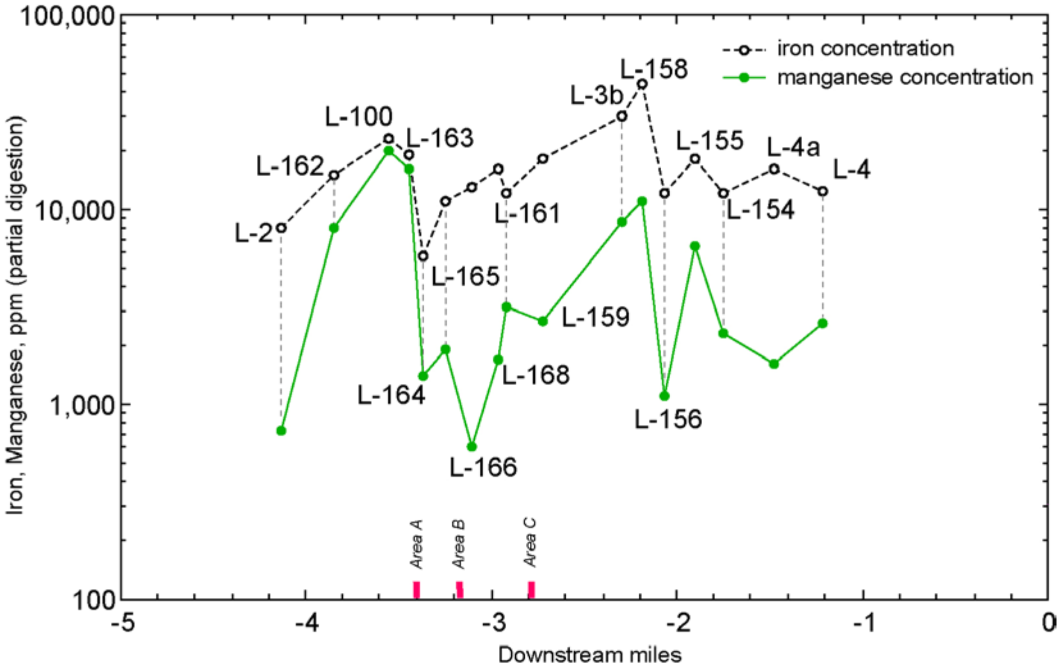


Figure 18. Downstream plot for iron and manganese concentrations (dilute-acid partial digestion) in streambed sediment of Frohner Meadows Creek and Lump Gulch.



Copper

Copper concentrations in the streambed sediment throughout Frohner Meadows are relatively low because the mineralized rock in the Frohner and Nellie Grant deposits has low concentrations of copper relative to the other ore-related metals. The CBPEC is 149 ppm; three sites exceeded that concentration (fig. 19). Site L-2 had a concentration of 19 ppm, slightly above the median-background copper concentration (15 ppm) for this study. Below the Frohner mill site, the concentration rises to 120 and 200 ppm at sites L-162 and L100, respectively. Dilution by streambed sediment reduces the concentration to 74 ppm at site L-164. Between L-165 and L-166, Frohner Meadows Creek passes through dispersed mill tailings (fig. 3) that increase the streambed-sediment concentrations. The addition of unenriched streambed sediment dilutes the copper concentration at L-161 at the lower end of upper Frohner Meadow. Site L-159 contained slightly more copper, possibly from the mill tailings impounded at the west end of lower Frohner Meadows (fig. 3). The R^2 correlation coefficients for iron and manganese on copper were only 0.48 and 0.50, respectively. Thus, copper is more likely transported as detrital weathering products or with organic matter to which it readily complexes.

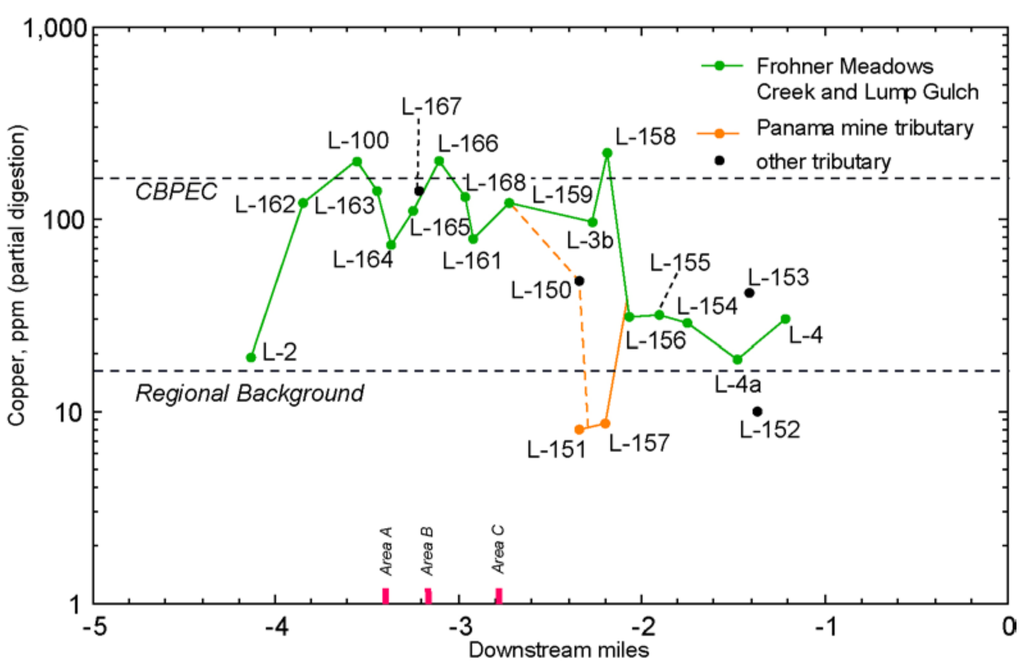
The concentration of copper at site 158 is much greater than at site L-3b. The cause of this increase, as seen in arsenic, manganese and iron, is not clear. Copper concentrations markedly decline between site L-158, just above the filled reservoir, and L-156, the outlet to the reservoir (fig. 19). Dilution by uncontaminated sediment from the Panama meadow tributary apparently reduces the dilute-acid extractable-copper concentrations in Frohner Meadows Creek sediment to 31 ppm at site L-156. Copper enrichments in the streambed sediment of Frohner Meadows present minor potential environmental effects as seen in their low levels of enrichment relative to regional background concentrations and crustal-abundance values; copper concentrations in Frohner Meadows exceed the CBPEC (149 ppm) at only a three sites.

Lead

Of the five ore-related metals discussed here, lead is the least soluble and least correlated to iron and manganese. The R^2 correlation coefficients for iron and manganese on lead were only 0.05 and 0.37 respectively. These low correlations imply that the transport of lead is as detrital material. Dilute-acid partial-digestion concentrations of lead from the streambed sediment probably represent primary galena (PbS) in the samples, as galena is readily soluble in the warm, dilute HCl used for the dilute-acid partial digestion.

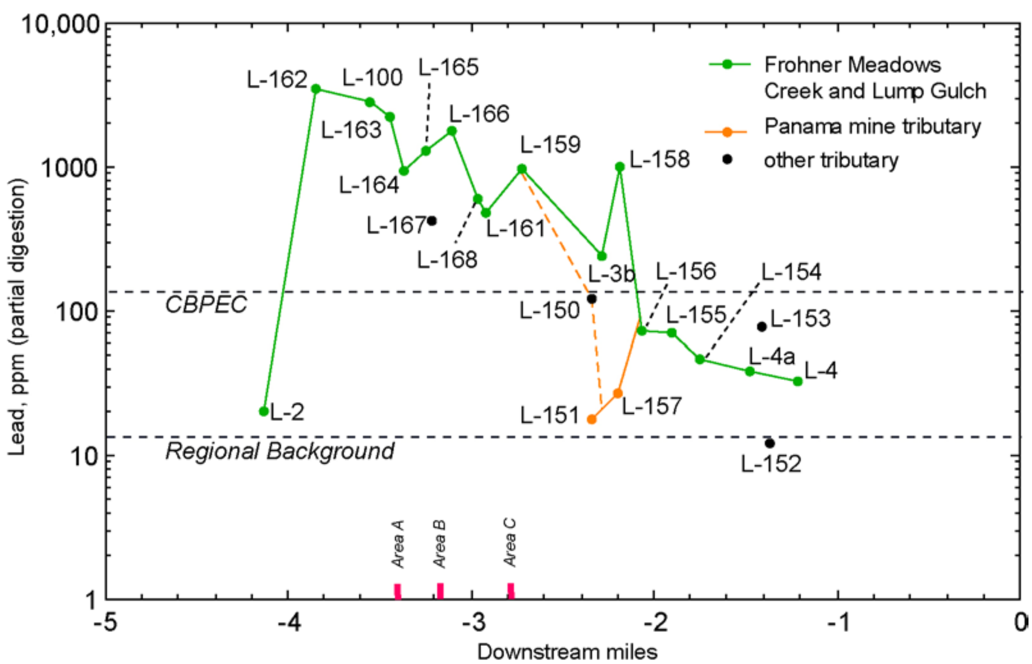
High concentrations of lead in streambed sediments of Frohner Meadows Creek are due to input from the Frohner mine and mill site (fig. 3). Above the mine (L-2), the dilute acid, partial-digestion concentration is low (20 ppm), close to the median-background concentration (12 ppm) and well below the CBPEC (128 ppm) (table 5, and fig. 20). Contribution of tailings material from the Frohner mill site (and probably from the Frohner mine, although a sample was not taken from directly below the mine site) increases the lead concentration in streambed sediment to 3,500 ppm at site L-162. Dilution by sediment from others sources produced a downstream decrease in the concentration at L-164 to 940 ppm. Dispersed mill tailings in the meadow between L-164 and L-166 contribute additional contaminated material that raises the lead concentration at L-166 to 1,800 ppm; dilution by other meadow sediment again lowers the lead concentration to 480 ppm at site L-161.

Figure 19. Downstream plot for copper (partial digestion) in streambed sediment of Frohner Meadows Creek and Lump Gulch.



A bulk sample of the fine-grained mill tailings (sample LFM 1) from the delta at the west end of lower Frohner Meadows contained 8,100 ppm total lead (table 6, Klein and others, 2003b). These mill tailings probably contribute to the increase in lead dilute-acid, partial-digestion concentration at site L-159 (960 ppm). The dilute-acid, partial-digestion lead concentration at site L-3b (220 ppm) is much lower, probably because only a small amount of detrital galena may be transported through lower Frohner Meadows. The meadow, with its numerous abandoned beaver ponds, ponds, and abundant marshes, is an effective detrital sediment trap under most stream-discharge conditions. The lead dilute-acid, partial-digestion concentration (1,000 ppm) at site L-158 is enigmatically high, as solution transport cannot be invoked to explain the large rise. One explanation is that a high-energy flushing event in the past moved fine-grained detrital lead through the meadows, and material with high lead concentrations settled out in the stream where there is a break in slope to a more gentle gradient (near site L-158). Dilution of lead concentrations at site L-156 by streambed sediment from the Panama Mine tributary is evident in figure 20. Note that the decrease for lead between sites L-158 and L-156 is higher than for cadmium (fig. 17). Since cadmium can be transported in solution, as well as in detrital grains, a higher proportion remains in streambed sediment downstream from the junction of the two creeks. The cadmium concentration drops by a factor of 5, whereas the lead concentration drops by a factor of about 14.

Figure 20. Downstream plot for lead concentration (dilute-acid partial digestion) in streambed sediment of Frohner Meadows Creek and Lump Gulch.



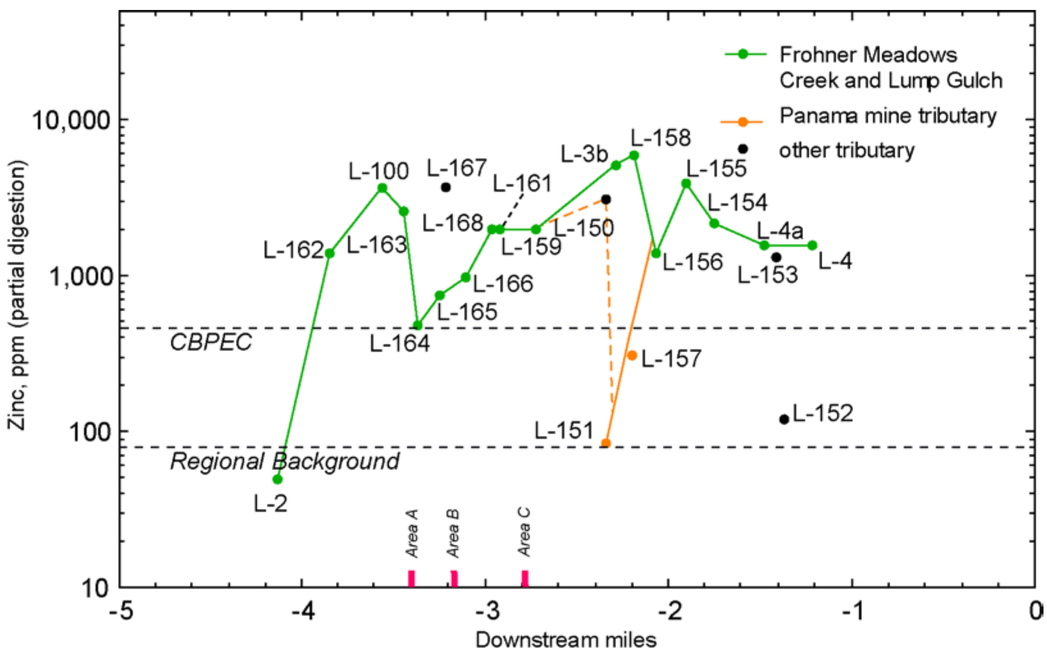
Zinc

Zinc exhibits isochemical behavior with cadmium. Cadmium commonly substitutes for zinc in sphalerite, the primary zinc-bearing ore mineral in the ore deposits near Frohner Meadows. The behavior of zinc in the streambed sediment in the study area is similar to that of cadmium. The dilute-acid, partial-digestion zinc concentration in streambed sediment above the Frohner mine and mill sites (L-2) is 49 ppm (fig. 21), below the median-background concentration of 80 ppm (table 4) and far below the CBPEC of 459 ppm (table 5). Below the Frohner mill site (L-162), the dilute-acid, partial-digestion zinc concentration in the streambed sediment (1,400 ppm) is higher than the total zinc concentration (400-1,100 ppm) in the mill waste material itself, and farther downstream at L-100, the dilute-acid, partial-digestion concentration (3,300 ppm) is higher still. This is probably due to enrichment by transport of dissolved zinc and scavenging by iron and(or) manganese oxyhydroxides. The R^2 correlation coefficients for iron and manganese on zinc were 0.86 and 0.71, respectively. Zinc is transported in the dissolved phase from the Frohner mine area on Frohner Meadows Creek and then is trapped by sediment grain coatings and concentrated in streambed sediment above site L-100.

As with the other metals, zinc concentrations are diluted from site L-100 downstream to site L-164 likely by unenriched streambed sediment from other sources. Between sites L-164 and L161, the zinc concentration increases again, probably from an influx from dispersed mill tailings between L-165 and L-166 and from the accumulation of zinc undergoing aqueous transport and scavenging by iron and manganese oxyhydroxides. The total zinc concentration of the mill tailings submerged at the west end of lower Frohner Meadows is 11,000 ppm (Klein and others, 2003b, table 6). It is not clear if there is direct transport of zinc to site L-159, as the dilute acid partial-digestion zinc concentration at that site is the same as at site L-161, which is upstream from the upper end of the meadow. However, since the dilute-acid, partial-digestion zinc concentration increases markedly downstream from site L-159 to over 4,600 ppm at site L-3b, it is probable that those mill tailings contribute some soluble zinc to the meadow that is then scavenged by iron and manganese oxyhydroxides near the east end of the meadow.

The familiar situation of dilution by sediment from the Panama Mine tributary is shown in figure 21. Note that the alternate path for the transport of dissolved zinc from the south side of lower Frohner Meadows through sites L-150 and L-157 is similar to that seen for cadmium. As with cadmium, iron, and manganese, the decrease in zinc concentration in streambed sediment below L-158 is only a factor of about 4, whereas lead was a factor of about 14, and arsenic was a factor of about 32. This again contrasts the behavior between the metals that substantially are transported in solution (cadmium, copper, and zinc) and those that are primarily clastic transported (arsenic and lead). Dilute-acid, partial-digestion zinc concentration increases downstream by site L-155, where the dilute-acid, partial digestion iron and manganese concentrations are high again, suggesting that iron and manganese-rich grain coatings have a significant role in accumulating dissolved zinc and cadmium from streamwater in this area.

Figure 21. Downstream plot for zinc concentrations (dilute-acid, partial digestion) in streambed sediment of Frohner Meadows and Lump Gulch.



HYDROLOGY

The recharge, movement, and discharge of water in the Frohner Basin (fig. 2) are influenced by many factors, including the climate, geology, and topography of the area. About 25 inches of annual average precipitation (U.S. Soil Conservation Service, 1977) provide recharge to ground-water flow systems and small streams that flow into Frohner Meadows. The steep slopes of granitic bedrock that surround Frohner Meadows and the relatively flat areas of unconsolidated sediment in Frohner Meadows form a unique hydrologic system that supports the wetland environment of Frohner Meadows. Ground-water and surface-water components of the hydrologic system were analyzed to estimate an annual hydrologic budget of Frohner Meadows and to understand the hydrologic regime of the wetlands.

Methods of Investigation

Hydrology of the area was investigated by analysis of surface-water flow, ground-water flow, and hydrogeologic characteristics of the area. A water budget was developed from site-specific measurements of discharge and aquifer characteristics and from regional values of precipitation and monthly discharge. Metal loads into and out of the Frohner Meadows area were estimated from measured values of stream discharge and metal concentrations. Seven shallow wells were installed in upper Frohner Meadows and three wells in lower Frohner Meadows for measurement of water levels and water quality. Seismic-refraction studies were completed along six lines across the wetland areas of the meadows and analyzed to estimate thickness of saturated unconsolidated sediment overlying the granitic bedrock.

Water-quality samples were collected from both surface- and ground-water sources in upper and lower Frohner Meadows. Surface-water samples typically were grab samples because discharge was too low to allow the use of a depth-integrating sampler. Filtered surface-water samples were processed onsite using a 0.45-micron syringe filter. Ground-water samples were collected from shallow wells using a peristaltic pump and filtered samples were processed onsite through a 0.45-micron capsule filter. All samples were processed according to procedures described in Wilde and others (1998) and were analyzed by the USGS National Water Quality Laboratory in Denver, Colorado. Analytical methods are described by Faires (1993), Fishman and Friedman (1989), Fishman (1993), Garbarino (1999), Garbarino and Struzeski (1998), Hoffman and others (1996), and Jones and Garbarino (1999).

Ground Water

The bedrock geology of Frohner Basin, the distribution and thickness of unconsolidated deposits, and the hydraulic characteristics of the unconsolidated deposits and plutonic bedrock that underlie the basin have a major control on local ground-water flow. Frohner Basin (fig.2) and the surrounding area are underlain entirely by plutonic rocks of the Boulder batholith which typically are quartz monzonite and granodiorite (Becraft and others, 1963). Nearly all porosity and permeability of the plutonic rocks are a result of fracturing and near-surface weathering. Outcrops of the Boulder batholith generally are considerably weathered, with large open fractures caused by weathering along existing joints. In many areas, joints in the rocks have sufficiently weathered to leave large, freestanding, rounded boulders. Weathering of the plutonic rocks rapidly decreases with depth, which is clearly evident in many road cuts, as well as mine workings, excavations, and drill holes. In the areas examined, the upper 5 ft (1.5 m) of rock typically are highly weathered with open joints. From about 5 to 50 ft (1.5 to 15 m), the plutonic rock grades from slightly weathered to unaltered rock, and most joints become tight, often with clay in the joints. Below about 50 ft, rocks of the Boulder batholith typically are fractured, although most fractures are extremely tight, and weathering is observed only on some fracture surfaces (McDougal and others, in press). Gouge typically accompanies even the smallest faults in the batholith (Becraft and others, 1963). Exceptions to these general characteristics may be found along some mineralized zones and large fractures. Hydraulic conductivity of the plutonic rocks typically is very low. At two core holes drilled west of the study area near the continental divide, hydraulic conductivities measured from slug tests were 0.02 ft/day and 0.04 ft/day (Maxim Technologies Inc., 1999). Both slug tests were conducted on fractured or weathered quartz monzonite of the Boulder Batholith at depths of 18–43 ft below the land surface. Because of decreasing hydraulic conductivity with depth, most ground-water flow in the Boulder batholith occurs in the uppermost-weathered zone.

Unconsolidated deposits in Frohner Basin include boulder till and colluvium on hillsides, and till, alluvium, volcanic ash, and organic deposits in the lowland areas of Frohner Meadows. During the Pleistocene epoch, glacial ice covered much of the highland area to the west of the study area. From the center of accumulation near upper Cataract Basin, ice moved eastward down Lump Gulch, North Fork Quartz Creek, and South Fork Quartz Creek, where the ice was joined by small tributary glaciers from poorly developed cirques in Frohner Meadows and Park Lake (Becraft and others, 1963). Before the Pleistocene epoch, the drainage from Frohner Meadows was through the North Fork of Quartz Creek; Lump Gulch captured this drainage during the Pleistocene (Becraft and others, 1963).

Moraines deposited by glacial ice dammed the preglacial channel of Frohner Meadows Creek, forming shallow ponds that subsequently filled with clay, silt, sand, volcanic ash, and organic deposits. Seismic-refraction soundings conducted along upper and lower Frohner Meadows (fig. 22) indicated that till and postglacial sediment overlying bedrock are as much as 45-ft (14-m) thick in upper Frohner Meadows and 25-ft (7.6-m) thick in lower Frohner Meadows. A major part of the unconsolidated deposits is till, based on large boulders exposed along the margins of the wetlands and from rocks and till encountered in auger holes drilled in the wetlands for installation of shallow test wells and in shallow meadow cores. Sediment overlying the till (in ascending order) typically are poorly sorted, angular, alluvial sand derived from batholith rocks, volcanic ash, organic-rich clay, and peat. Hydraulic conductivity of the organic-rich clay and volcanic ash is very low, and these materials function as confining layers for ground water in the thin underlying zone of alluvial sand.

The volcanic ash, tentatively identified as the Mazama ash, is a massive, tan biotitic air-fall deposit. The age of the Mazama ash has been estimated by ^{14}C dating to be about 7 Ka (Bacon, 1983) and provides an approximate age for the beginning of the development of postglacial ponds. This unit was observed in six cores in Frohner Meadows, ranged in depth from 60 to 135 cm (2 to 4.4 ft) below the present surface, and was from 4- to 25-cm (0.1 to 0.8 ft) thick where it was encountered.

Discharge of ground water from unconsolidated deposits plays an important role in maintaining the wetland environment of Frohner Meadows. Ground water moves from topographically higher areas within Frohner Basin, flows predominantly through thin unconsolidated deposits and the uppermost weathered zone at the top of bedrock, and discharges to land surface in wetland areas of Frohner Meadows. Ground-water discharge, in the form of numerous seeps, was observed along the west, north, and east margins of upper Frohner Meadows and along the west margin of lower Frohner Meadows. A large upward component of ground-water flow was documented by comparing water levels measured in shallow (total depths 5–9 ft) test wells on Sept. 26, 2001, with surveyed elevations of land surfaces and nearby water surfaces (table 6). Ground-water levels were above land surface at three wells (FM-4, FM-5, and FM-7) and were above the adjacent pond or stream surface at three other wells (FM-1, FM-3, and FM-8). Upward hydraulic gradients were as much as 0.33 (1.05 ft/3.0 ft) at well FM-5.

Discharge of ground water to wetlands in Frohner Meadows contributes to stream discharge in Frohner Meadows Creek. Discharge measurements were made at 12 sites on Frohner Meadows Creek and its tributaries (fig. 22) several times in 2001. Small gains in discharge were measured in the downstream part of upper Frohner Meadows. Between measurement sites H and I, discharge on June 26, 2001, increased from 0.76 ft^3/sec to 0.86 ft^3/sec and on October 10, 2001, discharge increased from 0.09 ft^3/sec to 0.15 ft^3/sec. Measurements made on other dates or sites indicated small increases or small decreases in discharge through different sections of Frohner Meadows. Many of the differences in discharge were within measurement error of the methods used. However, ground water likely discharges to Frohner Meadows Creek over much of the length of the wetlands based on observed flow of seeps toward the stream and measured ground-water levels that generally are above stream surface or land surface.

Downstream from lower Frohner Meadows, discharge of ground water through moraine and bedrock is small, based on generally low-hydraulic conductivities of till and batholith rocks. A likely range of hydraulic conductivity, based on measured hydraulic conductivity in the Boulder batholith (Maxim Technologies, Inc., 1999) and published values for till (Bouwer, 1978), is 0.003 to 0.3 ft/day with a median value of 0.03 ft/day. Calculated flow (Darcy equation, see Lohman, 1972) of ground water through till and the upper weathered zone of bedrock ranges from 0.0001 to 0.01 ft^3/s, with a median of 0.001 ft^3/s, based on the above values of hydraulic conductivity, a width of 600 ft, a thickness of 60 ft, and a gradient of 0.1 (80ft/800ft).

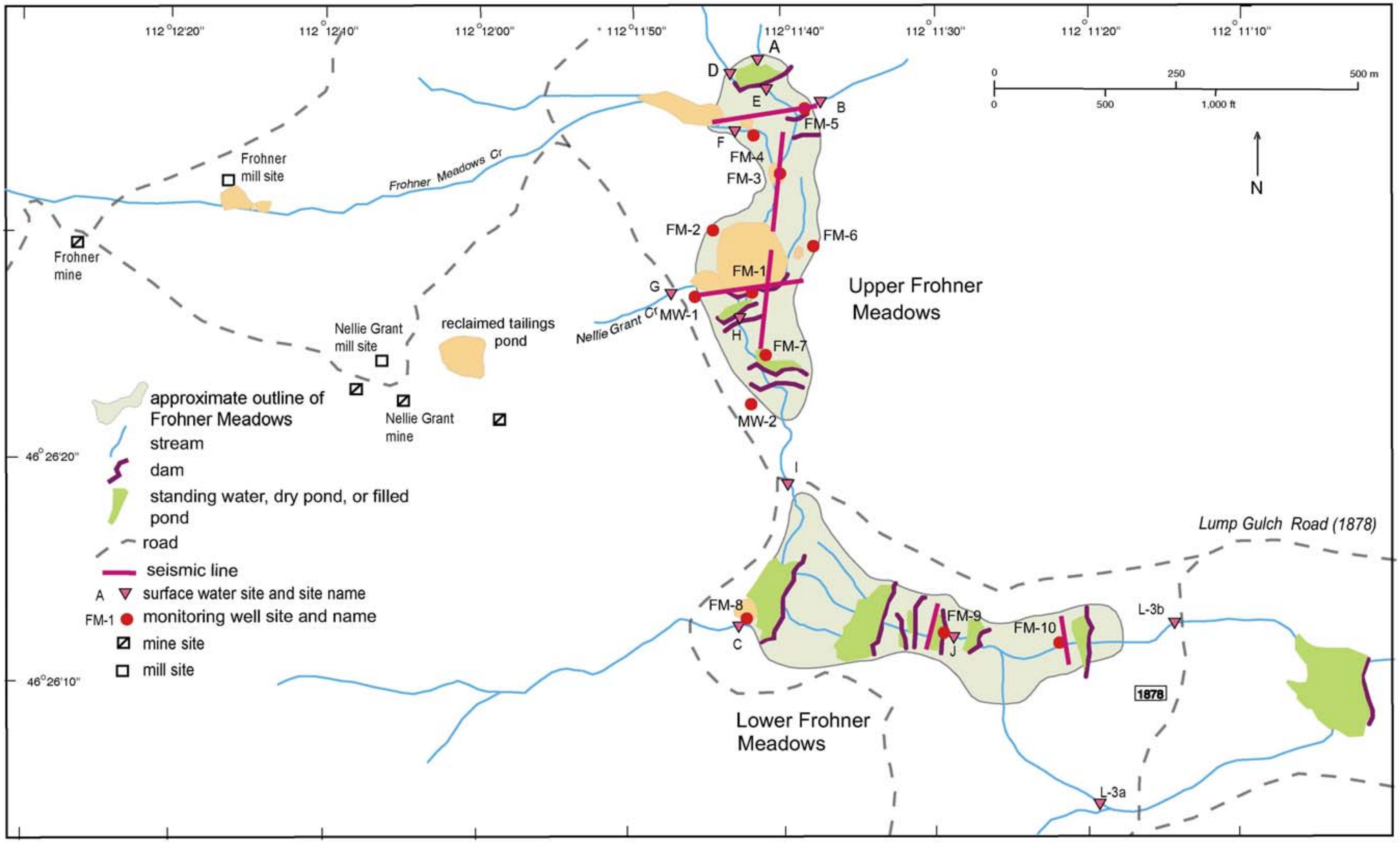
Surface Water

Frohner Basin is drained by Frohner Meadows Creek, which drains into Lump Gulch and eventually into Prickly Pear Creek (fig 3). Frohner Meadows Creek flows adjacent to the Frohner mine and enters the wetlands of upper Frohner Meadows in the northwestern part of the meadows. Several small tributaries join Frohner Meadows Creek, including an unnamed tributary that drains from the Nellie Grant mine reclamation area. All water that drains from upper Frohner Meadows flows into lower Frohner Meadows via Frohner Meadows Creek. In the western part of lower Frohner Meadows, a small tributary that drains the steep slopes west of the meadows joins Frohner Meadows Creek. In the eastern part of lower Frohner Meadows, Frohner Meadow Creek splits at a beaver pond into two separate outflow channels. The two channels eventually rejoin in Lump Gulch. The drainage area of Frohner Meadows Creek at the outlet of upper Frohner Meadows is 1.04 square miles. At the outlets of lower Frohner Meadows, the creek has a drainage area of 1.30 square miles. The drainage area of lower Frohner Meadows was measured as all drainage area upstream from the Jefferson County Road 1878, where it crosses Frohner Meadows Creek (near sites L-3a and L-3b on fig. 22).

Frohner Meadows Creek has no gaging station that can be used to measure daily, mean-monthly, or annual-discharge values; therefore, regression equations (Parrett and Johnson, 1989) that relate monthly discharge characteristics to drainage area and mean annual precipitation were used to estimate mean-monthly and annual discharge. The regression equations yielded a mean annual discharge of 0.98 ft^3/s for Frohner Meadows Creek at the outlet of lower Frohner Meadows. Calculated mean-monthly discharge ranged from 0.19 ft^3/s in January to 3.8 ft^3/s in May (table 7).

Base flow of Frohner Meadows Creek, which is derived from ground-water discharge, also was estimated from measured discharge in nearby streams that drain the areas underlain by the Boulder batholith and have geologic conditions similar to the study area. Base flow of Basin Creek, Cataract Creek, and High Ore Creek, determined from winter measurements made from 1996–2000 (Nimick and Cleasby, 2000; T.E. Cleasby, unpublished data), averaged 0.11 ft^3/s from each square mile of drainage area. Assuming that Frohner Meadows Creek has similar runoff characteristics, discharge at the outlet of lower Frohner Meadows would be about 0.15 ft^3/s during base-flow conditions. Actual discharge of Frohner Meadows Creek measured during base-flow conditions on October 11, 2000, was 0.11 ft^3/s at site L-3 (sites L-3a and L-3b combined, fig. 22). Based on both calculated and measured values of stream discharge, ground-water discharge is estimated to contribute about 0.15 ft^3/s to Frohner Meadows Creek during base-flow conditions. A larger volume of ground water discharges into Frohner Meadows Creek during and after large rainfall events and spring snowmelt.

Figure 22. Location of monitoring-well sites, seismic lines, and surface-water sites in and near Frohner Meadows.



Water Budget

An annual-water budget for Frohner Meadows and Frohner Basin was developed to evaluate relative volumes of water that discharge through surface water, ground water, and evapotranspiration. This budget was developed using published values of long-term precipitation and evaporation and calculated values of stream discharge and ground-water flow. Calculations of stream discharge and ground-water flow were based on the hydrologic conditions of the study area. Frohner Basin is located at the headwaters of Lump Gulch, and because of its location at the uppermost part of the drainage, all water entering Frohner Meadows likely originates as precipitation within the 1.30 square mile Frohner Basin.

This annual-water budget for the basin assumes that long-term changes in storage are zero and that the budget may be expressed as a simple mass-balance equation where precipitation is equal to all outflows:

Precipitation = Stream discharge + Ground-Water Discharge + Evapotranspiration (equation 1)

Average annual precipitation for the area between Frohner Meadows and the basin divide is about 25 inches (U.S. Soil Conservation Service, 1977). Average-annual volume of precipitation that falls on Frohner Basin is about 1,733 acre-ft, and this volume of water equals all outflows from the basin. The stream-discharge component of the annual budget is about 0.98 ft^3/s (709 acre-ft/year) of which at least 0.15 ft^3/s (108 acre-ft/year) originates as ground-water flow within the basin. Ground water that leaves the basin as flow through till and granite is estimated at about 1 acre-ft/year, although it could range from 0.09 to 9 acre-ft/year. A large volume of water leaves Frohner Basin through evapotranspiration. Potential evapotranspiration rates for wetlands are greater than for forest or grassland; therefore, total evapotranspiration for the basin is subdivided into evapotranspiration from wetland and evapotranspiration from forest.

Evapotranspiration for the wetland area of Frohner Meadows can be calculated as a free-water-surface evaporation and is about 30 inches/year (National Oceanic and Atmospheric Administration, 1982). Actual evapotranspiration from the wetlands probably is only slightly less than potential evaporation because of the large areas of ponded water, wet soils, and vegetation with unlimited water supply. Evapotranspiration of 30 inches/year from the 29.7 acres of wetlands of Frohner Meadows is equivalent to 74 acre-ft/year. Evapotranspiration from the 802 acres of forest and grasslands in the Frohner Basin can be calculated as a remainder in equation 1. Rearranging equation 1:

$$\textit{Precipitation} - \textit{Stream discharge} - \textit{Ground-water discharge} - ET_{wetland} = ET_{forest}$$

(equation 2)

Substituting acre-ft /year values into equation 2:

1733 - 709 – 1 –74 = 949 acre-ft/year

The 949 acre-ft/year of evapotranspiration from the 802 acres of forest or grass is equivalent to a rate of 14 inches/year of evapotranspiration over that area, or slightly less than one-half the rate for wetlands. The water budget for Frohner Basin is summarized below in table 8.

Table 6. Water-level data for wells and surface-water sites in Frohner Meadows, September 24–26, 2001.

[Relative elevations (in ft) were surveyed from temporary benchmarks; bench mark elevations estimated from 1:24,000 scale topographic map, NGVD of 1929.]

Site Name	Elevation of land surface	Water level below land surface [1]	Date measured	Elevation of water surface
Well FM-1	6582.13	0.96	9/26/2001	6581.2
Well FM-2	6583.79	1.10	9/26/2001	6582.7
Well FM-3	6587.29	0.79	9/26/2001	6586.5
Well FM-4	6597.89	+0.43	9/26/2001	6598.3
Well FM-5	6595.11	+1.05	9/26/2001	6596.2
Well FM-6	6583.76	1.97	9/26/2001	6581.8
Well FM-7	6576.51	+0.16	9/26/2001	6576.7
Well FM-8	6541.55	0.45	9/26/2001	6541.1
Well FM-9	6530.03	1.10	9/26/2001	6528.9
Well FM-10	6517.50	0.76	9/26/2001	6516.7
Frohner meadows creek west of well FM-1 (water surface)			9/24/2001	6580.7
Beaver pond at well FM-7			9/24/2001	6575.9
Beaver pond between wells FM-1 and FM-7			9/24/2001	6579.2
Stream west of well FM-6 (water surface)			9/24/2001	6581.9
Frohner meadows creek east of well FM-2			9/24/2001	6582.7
Frohner meadows creek by well FM-3			9/24/2001	6585.3
Frohner meadows creek, north of well FM-4			9/24/2001	6597.1
Frohner meadows creek between wells FM-4 and FM-5			9/24/2001	6595.2
Beaver pond at well FM-5			9/24/2001	6593.8
Upper beaver pond in upper Frohner Meadows			9/24/2001	6600.0
Beaver pond at well FM-8			9/24/2001	6540.1
Stream at well FM-9 (water surface)			9/24/2001	6528.9
Beaver pond between wells FM-9 and FM-10			9/24/2001	6526.0
Stream at well FM-10 (water surface)			9/24/2001	6516.7

[1] Water level below or above (+) land surface

Table 7. Calculated mean-monthly discharge of Frohner Meadows Creek.

Month	ft^3/second	Acre-ft
October	0.39	24
November	0.28	17
December	0.23	14
January	0.19	12
February	0.20	11
March	0.25	16
April	0.97	58
May	3.8	234
June	3.3	197
July	1.0	63
August	0.61	38
September	0.43	25
Annual	0.98	709

Table 8. Summary of annual-water budget of Frohner Basin.

Source	Volume (acre-ft) of inflow (+) or outflow (-)	Percent of annual inflow or outflow
Precipitation of 25 inches per year on 832 acres	+ 1,733	+ 100
Discharge from Frohner Meadows Creek; drainage area of 1.30 square miles	- 709	- 41
Ground-water flow to Frohner Meadows Creek; included in stream-discharge volume and percent values	(> 108)	(> 6)
Ground-water flow out of basin through till and bedrock	- 1	<1
Potential evapotranspiration from 29.7 acres of wetland	- 74	- 4
Evapotranspiration from 802 acres of forest and grass	- 949	- 55

WATER QUALITY

Samples of ground water and surface water from 22 sites in Frohner Basin were analyzed for specific conductance, pH, common ions, and trace metals. Ground-water sampling sites were selected to sample the quality of (1) ground water flowing into Frohner Meadows from various sources, (2) ground water flowing out of upper and lower Frohner Meadows, and (3) ground water beneath mill tailings deposits in the wetland areas of Frohner Meadows. Surface-water sites were selected to sample all inflows and outflows as well as measure changes in water quality within Frohner Meadows. Trace-element loads through Frohner Meadows were calculated from discharge and water-quality data.

Ground Water

Ground water was sampled at 10 wells in upper and lower Frohner Meadows (sites FM-1 through FM-10 on fig. 2); data are in Klein and others, 2003b. Well logs containing lithologic descriptions and well completion information can be found in Klein and others (2003b). All wells were sampled on July 26, 2001, the day after they were purged with a bailer. Four wells (FM-1, FM-3, FM-7, and FM-10) were sampled a second time on October 17, 2001.

Specific conductance of ground water measured onsite while sampling ranged from 144 µS/cm at well FM-5 to 233 µS/cm at well FM-8. Onsite values of pH ranged from 6.0 at well FM-6 to 7.6 at well FM-4. Calcium was the predominant cation in all water from wells.

Dissolved arsenic was present in most (10 out of 14) water samples in concentrations exceeding the Montana numeric water-quality standard for human health of 20 ug/L in ground water (Montana Department of Environmental Quality, 2002). High concentrations of dissolved arsenic were present in water samples from wells FM-1, FM-4, FM-7, FM-8, FM-9, and FM-10. The largest concentration of arsenic was measured in a water sample collected on October 17, 2001, from well FM-1 (3,380 µg/L), completed in an area of mill tailings in the central part of Upper Frohner Meadows (Area A). Water from well FM-4, which is completed in the large impoundment of mill tailings where Frohner Meadows Creek enters the west margin of upper Frohner Meadows, also had a high concentration of arsenic (414 µg/L). Water samples collected on July 26, 2001, from wells FM-2, FM-5, and FM-6 on the west, northeast, and east margins of upper Frohner Meadows had the smallest concentrations of arsenic, which ranged from 1.0 µg/L at FM-5 to 13.2 µg/L at FM-6 (Klein and others, 2003b).

Concentrations of dissolved cadmium, copper, and lead were low in water samples from all wells and were below human-health standards established by the Montana Department of Environmental Quality (2002). Dissolved zinc ranged from less than 1 µg/L in a sample from well FM-3 to 419 µg/L in a sample from well FM-9.

Water-quality data are available for two additional wells in the area; well MW-1 located just west of the central part of upper Frohner Meadows, adjacent to Nellie Grant Creek, and well MW-2 located on private property near the southwestern part of upper Frohner Meadows (fig. 2). Well MW-1 reportedly is screened between 13.5 and 25 ft below land surface in unconsolidated deposits and weathered bedrock and had a depth to water of about 5 ft below land surface, which is lower than the stream level in this area (Pioneer Technical Services, 1996). Well MW-2 completed in granitic bedrock is greater than 100 ft deep and is artesian, flowing approximately 1–2 gallons per minute (Pioneer Technical Services, 1996). Five water samples collected from MW-1 had very high mean concentrations of cadmium (79 µg/L) and zinc (9,300 µg/L). Mean concentrations of arsenic, copper, and lead in MW-1 were fairly low (Klein and others, 2003b. The high concentrations of cadmium and zinc measured for MW-1 likely are from infiltration of water from Nellie Grant Creek (see below), as the well is near the creek, and concentrations of dissolved cadmium and zinc in the stream are similar to those in ground water at the well. Water samples from the deeper well MW-2 had low concentrations of arsenic, cadmium, copper, lead, and zinc.

Surface Water

Surface water was sampled at 12 sites in the Frohner Meadows area (fig. 22). Surface-water-quality data are in Klein and others (2003b, table 6). Sample sites A, B, C, and D are located on small tributaries that flow into the wetlands of Frohner Meadows; these tributaries drain areas that appear to have minimal or no disturbance from mining. Sample site F is on Frohner Meadows Creek, and site G is on Nellie Grant Creek. Sample sites E, H, I, and J were selected to show potential changes in quality as water moved downstream through Frohner Meadows and its mill tailings deposits. Sample sites L-3a and L-3b are located on the two outflows from lower Frohner Meadows.

Specific conductance ranged from 33 µS/cm at tributary inflow site C to 500 uS/cm at site G on Nellie Grant Creek. In general, specific conductance of all tributary inflows except Nellie Grant Creek was less than 100 µS/cm, and specific conductance of water discharging from lower Frohner Meadows (sites L-3a and L-3b) ranged from 88 to 483 µS/cm. Field measurement of samples indicated mostly neutral pH values with both the lowest (6.0) and highest (8.2) values measured from samples collected at site L-3b.

Concentrations of trace metals in tributaries to Frohner Meadows greatly vary by source of inflow (table 9). Small tributaries sampled at sites A, B, C, and D typically had low concentrations of arsenic, cadmium, copper, lead, and zinc. Frohner Meadows Creek, which drains the area of the Frohner mine, had higher concentrations of trace metals than the small tributaries. The highest concentrations of trace metals were measured in Nellie Grant Creek, which drains the adits and reclaimed area of the Nellie Grant mine. High concentrations of trace metals were measured in Frohner Meadows Creek in the area from the mill tailings deposits in upper Frohner Meadows to the outlets of lower Frohner Meadows.

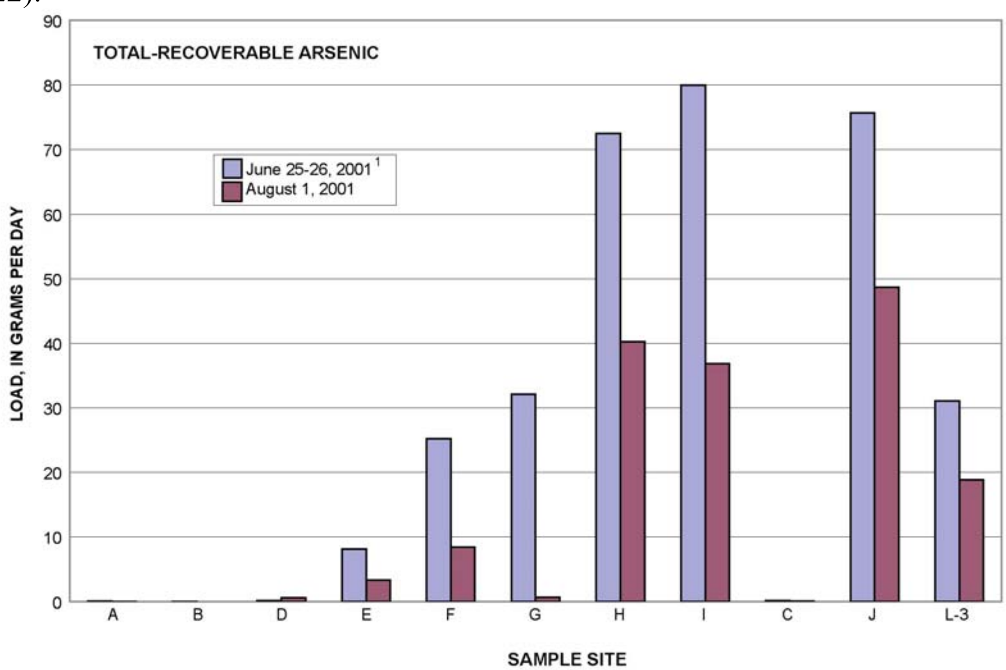
Total-recoverable arsenic concentrations ranged from less than 2 µg/L in samples from tributaries A and B, to 208 µg/L in a sample from Nellie Grant Creek. The total-recoverable arsenic concentration measured in a sample from Nellie Grant Creek exceeds the chronic aquatic-life standard of 150 µg/L (Montana Department of Environmental Quality, 2002). Total-recoverable cadmium concentrations ranged from about 0.03 µg/L in samples from tributary sites A and C to 121 µg/L in a sample from Nellie Grant Creek. Total-recoverable copper concentrations ranged from 2.2 µg/L in a sample from tributary site A to 83.9 µg/L in a sample from Nellie Grant Creek. Total-recoverable lead concentrations ranged from <1 µg/L in samples from tributary sites A, B, and C to 72 µg/L in a sample from Nellie Grant Creek. Total-recoverable zinc concentrations ranged from 2 µg/L in a sample from tributary site C to 15,100 µg/L in a sample from Nellie Grant Creek. At most sites along Frohner Meadows Creek and areas downstream from Nellie Grant Creek concentrations of tota- recoverable cadmium, copper, lead, and zinc exceeded Montana aquatic life standards (Montana Department of Environmental Quality, 2002).

Trace-Metal Loads

Instantaneous loads of trace metals into and out of Frohner Meadows were calculated from instantaneous stream-discharge measurements and measured concentrations of total-recoverable trace metals in water samples. Calculated loads are reported in grams per day (table 9). Graphs of instantaneous loads of total-recoverable arsenic, cadmium, copper, lead, and zinc are shown in figures 23–27 for two sampling periods. The first set of samples was collected on June 25 and 26, 2001 at all sites except L-3. A sample for site L-3 (L-3a and L-3b combined) was collected on May 10, 2001 at a time of slightly greater discharge than the June samples. The second set of samples was collected on August 1, 2001, at a time of low-stream discharge.

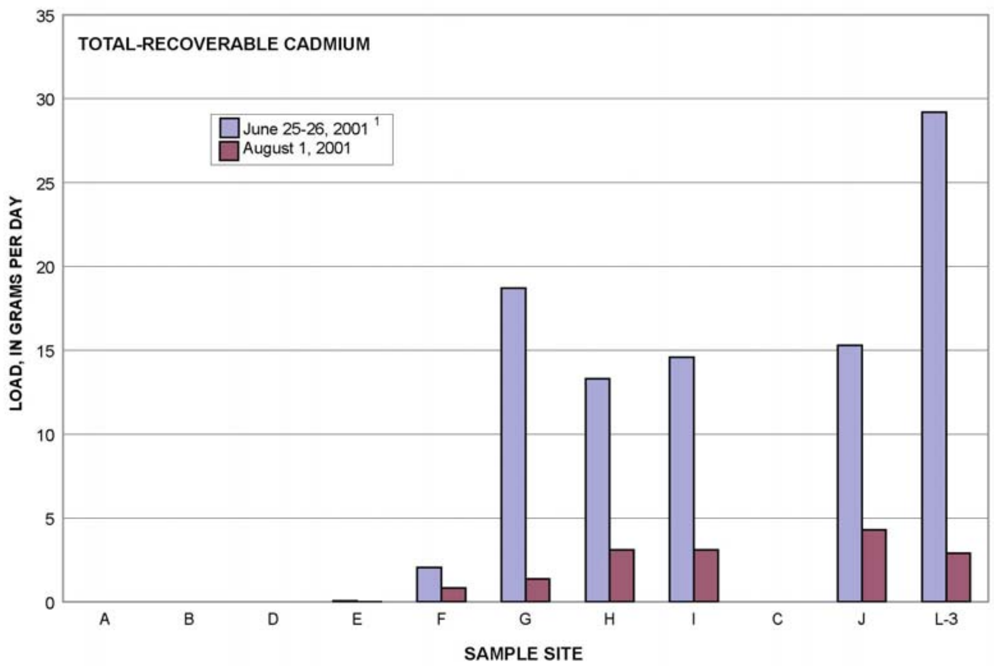
Small tributaries sampled at sites A, B, C, and D had small loads of trace metals for both the June and August sample sets. The larger tributaries of Frohner Meadows Creek, where it enters upper Frohner Meadows (site F), and Nellie Grant Creek (site G) contributed the largest loads of total-recoverable arsenic, cadmium, copper, lead, and zinc to upper Frohner Meadows. Sample site E, which discharges from the uppermost beaver pond in upper Frohner Meadows, also contributed small loads of total-recoverable arsenic, copper, and lead (figs. 23–27). The largest arsenic loads were measured in Frohner Meadows Creek at sites H, I, and J, which are downstream from Nellie Grant Creek and the mill tailings deposits in the central part of upper Frohner Meadows. Arsenic loads at sites H and I were greater than the sum of upstream tributaries, which indicates that additional arsenic is entering Frohner Meadows Creek from mill tailings and ground water in that area. A major part of the total-recoverable cadmium load in Frohner Meadows Creek was contributed by Nellie Grant Creek (site G). Cadmium load in Frohner Meadows Creek (June 25–26 sample) substantially increased downstream from the confluence with Nellie Grant Creek and remained high downstream in samples collected at sites H, I, and J (fig. 24). Loads of total-recoverable copper, lead, and zinc also remained high at downstream sample sites H, I, and J (figs. 25–27).

Figure 23. Instantaneous loads of total-recoverable arsenic (site locations shown in figure 22).



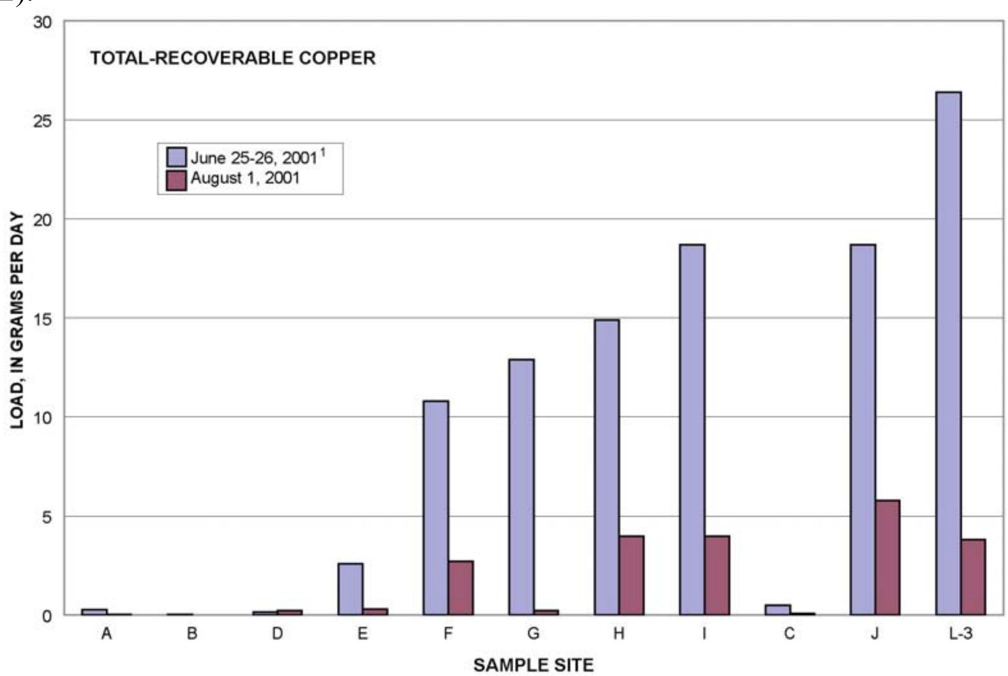
1) sample at L-3 collected on May 10, 2001

Figure 24. Instantaneous loads of total-recoverable cadmium (site locations shown in figure 22).



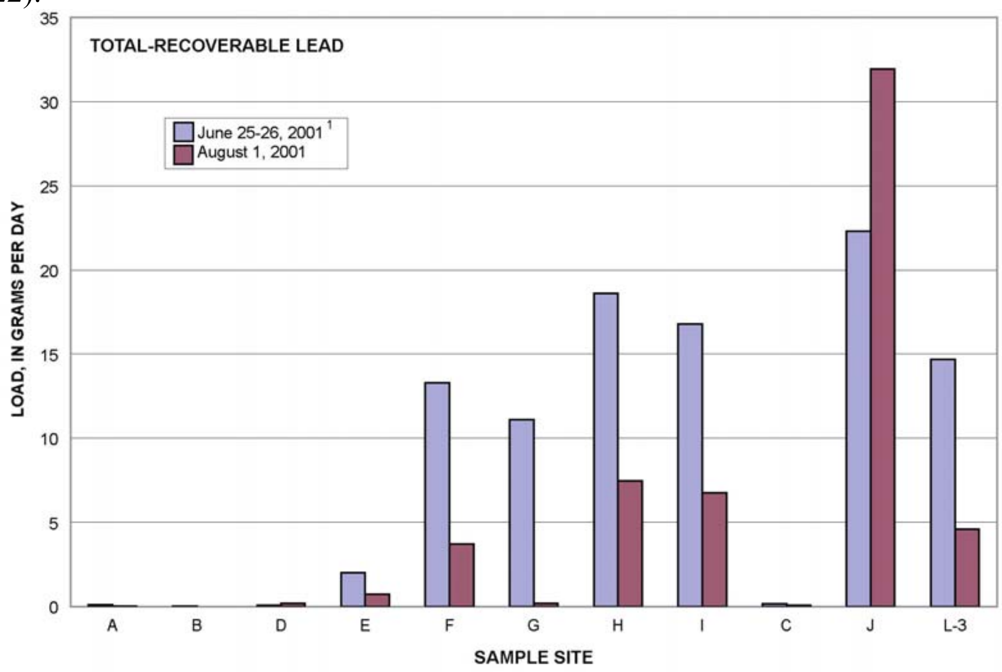
1) sample at L-3 collected on May 10, 2001

Figure 25. Instantaneous loads of total-recoverable copper (site locations shown in figure 22).



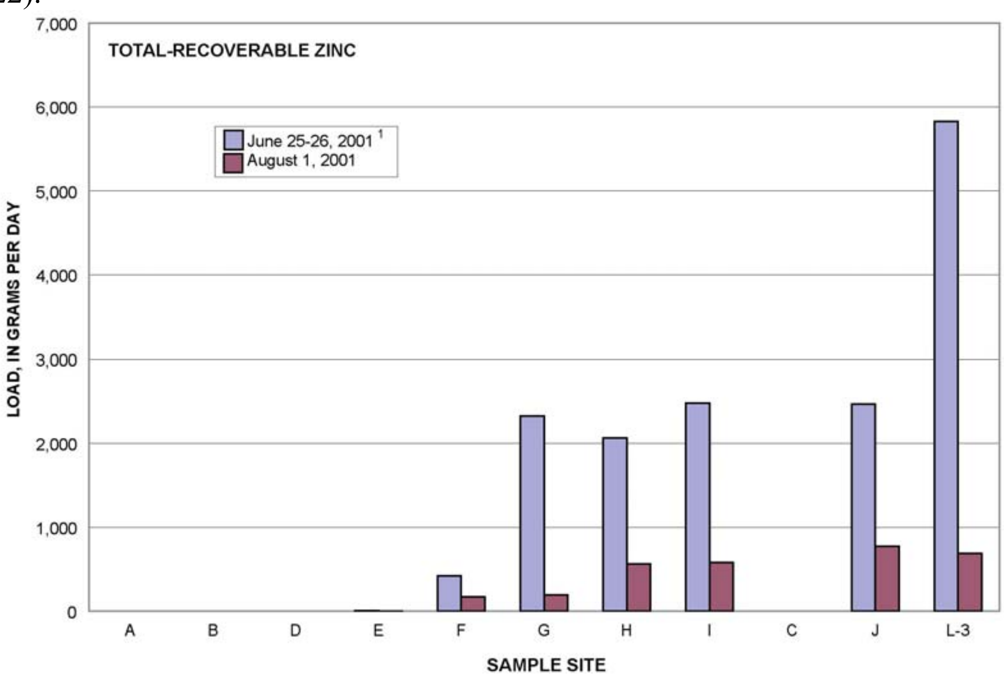
1) sample at L-3 collected on May 10, 2001

Figure 26. Instantaneous loads of total-recoverable lead (site locations shown in figure 22).



1) sample at L-3 collected on May 10, 2001

Figure 27. Instantaneous loads of total-recoverable zinc (site locations shown in figure 22).



1) sample at L-3 collected on May 10, 2001

Table 9. Concentrations and instantaneous loads of total-recoverable trace metals in the Frohner Meadows area..

[*Load (grams per day) = discharge (cubic ft/second)* x *concentration (micrograms/liter)* x *2.4466,symbols: E, estimated; <, less than]*

Site ID	Site name	Date	Time	Instantaneous discharge	Total-recoverable arsenic	Arsenic load	Total-recoverable cadmium	Cadmium load	Total-recoverable copper	copper load	Total-recoverable lead	lead load	Total-recoverable zinc	Zinc load
				(cu ft/sec)	(ug/L)	(g/day)	(ug/L)	(g/day)	(ug/L)	(g/day)	(ug/L)	(g/day)	(ug/L)	(g/day)
462638112114201	A	6/25/2001	1255	0.0353	E1	E0.09	E0.03	E0.002	3.2	0.28	<1	<0.09	4	0.35
		8/1/2001	945	0.00353	2	0.02	E0.03	E0.0002	2.2	0.02	<1	<0.009	5	0.04
462636112113801	B	6/25/2001	1340	0.00353	<2	<0.02	0.07	0.001	3.0	0.03	<1	<0.009	3	0.03
462637112114401	D	6/26/2001	910	0.0162	3	0.12	0.05	0.002	4.1	0.16	2	0.079	7	0.28
		8/1/2001	1020	0.027	9	0.59	0.07	0.005	3.3	0.22	3	0.198	11	0.73
462637112114101	E	6/26/2001	945	0.2066	16	8.09	0.12	0.061	5.1	2.58	4	2.02	20	10.1
		8/1/2001	1050	0.0247	55	3.32	0.13	0.008	5.0	0.30	12	0.725	21	1.27
462635112114401	F	6/26/2001	1005	0.6048	17	25.2	1.40	2.07	7.3	10.8	9	13.3	284	420
		8/1/2001	1135	0.138	25	8.44	2.49	0.84	8.0	2.70	11	3.71	505	171
462627112114701	G	6/26/2001	1040	0.063	208	32.1	121	18.7	83.9	12.9	72	11.1	15,100	2,330
		8/1/2001	1240	0.006	45	0.66	94.0	1.38	15.9	0.23	13	0.191	13,400	197
462626112114301	H	6/26/2001	1115	0.76	39	72.5	7.16	13.3	8.0	14.9	10	18.6	1,110	2,060
		8/1/2001	1205	0.203	81	40.2	6.23	3.09	8.0	3.97	15	7.45	1,130	561
		10/16/2001	1105	0.09	52	11.5	7.92	1.74	6.4	1.41	9	1.98	1,920	423
462619112114001	I	6/26/2001	1200	0.86	38	80.0	6.94	14.6	8.9	18.7	8	16.8	1,180	2,480
		8/1/2001	1350	0.212	71	36.8	6.00	3.11	7.7	3.99	13	6.74	1,120	581
		10/16/2001	1140	0.15	23	8.44	8.96	3.29	5.4	1.98	4	1.47	2,320	851
462613112114401	C	6/25/2001	1540	0.0671	E1	E0.16	E.03	E0.005	3.0	0.49	<1	<0.16	2	0.33
		8/1/2001	1420	0.01	4	0.10	.06	0.001	2.8	0.07	3	0.073	6	0.15
462612112113001	J	6/26/2001	1300	0.91	34	75.7	6.89	15.3	8.4	18.7	10	22.3	1,110	2,470
		8/1/2001	1500	0.311	64	48.7	5.66	4.31	7.6	5.78	42	32.0	1,020	776
462603112112101	L-3a	6/16/2000	1415	0.62	6	9.10	6.31	9.57	7.4	11.2	2	3.03	1,450	2,200
		10/11/2000	1345	0.0003	10	0.01	9.76	0.01	2.7	<0.001	<1	<0.001	3,970	2.91
		5/10/2001	1100	0.26	7	4.45	6.67	4.24	7.3	4.64	2	1.27	1,630	1,040
		8/1/2001	1130	0.004	11	0.11	5.21	0.05	6.9	0.07	2	0.020	1,360	13.3
462612112111501	L-3b	6/16/2000	1445	1.17	15	42.9	13.1	37.5	11.0	31.5	8	22.9	2,650	7,590
		10/11/2000	1630	0.11	6	1.61	47.1	12.7	5.8	1.56	4	1.08	15,400	4,150
		3/15/2001	1130	0.06	17	2.50	15.6	2.29	10.3	1.51	9	1.32	4,720	693
		5/10/2001	1120	0.78	14	26.7	13.1	25.0	11.4	21.8	7	13.4	2,510	4,790
		8/1/2001	0950	0.233	33	18.8	4.99	2.84	6.5	3.71	8	4.56	1,190	678

SUMMARY

Frohner mine and mill tailings typically contain the highest concentrations of arsenic and lead in the study area, as seen in total-metal concentrations in bulk samples and core material downstream from the Frohner mill. Results of the EPA leach-procedure (Klein and others, 2003b) show that the high summed concentrations of ore-related metals are dominated by lead. Analyses of two size fractions from material in mill tailings from Area A show that coarse quartz chips (>2-mm), that probably are unprocessed ore also contain high concentrations of lead and relatively low concentrations of zinc; the coarse fraction also has a higher acid-generating capacity than the finer fraction, probably the result of the presence of unweathered pyrite in the quartz chips that was not removed during ore processing. Fine-grained material (<2-mm) from Area A has a low acid-generating capacity (table 1) and lower-summed metal concentrations. Bulk-mine waste and mill tailings from the Nellie Grant mine and mill contain high concentrations of cadmium and zinc relative to similar material from the Frohner mine and mill as seen in bulk analyses of the debris fan below Nellie Grant Creek. Acid-generating capacity is low for all surface samples of mill tailings in Area B (fig. 3) and material of mixed sources from the Nellie Grant and Frohner mines.

The acid-generating capacity of material from the mill-tailings delta in lower Frohner meadows is extremely high (table 1) relative to other waste material in the study area and elsewhere. Oxidation of this material, which might occur if water levels were lowered, would generate acidic, metal-rich water. The fine grain size of this unencapsulated material will enhance its susceptibility to weathering. This material is likely to contribute metals as dissolved or suspended constituents in surface water and ground water or as adsorbed material or colloids in streambed sediment in lower Frohner Meadows and upper Lump Gulch. These mill tailings have large concentrations of readily leachable arsenic, cadmium, and zinc based on the EPA 1312 leach data of surface samples and probably contribute to the solution-transported load of metals in surface water in lower Frohner Meadows. The effects of acid generated by oxidation of this material could be mitigated by the neutral and mildly alkaline nature of the surface water in the study area (see table 4, Klein and others, 2003b) and the probable high acid-neutralizing capacity of the local bedrock. The granitic rocks of the Boulder batholith that underlie the study area have a high capacity for neutralizing acid that results in characteristically neutral to mildly alkaline pH in surface water and the rapid neutralization of acid produced from anthropogenic and natural sources (Desborough and others, 1998).

Mine waste in Area A (fig. 3) is present in the debris fan at the edge of upper Frohner Meadows and material that has been deposited below the fan in the meadow proper near the east end of line 1 and near line 2. In most cases, mine waste, characterized by coarse quartz lag deposits that probably are untreated ore from the Frohner mill, is mixed with fine-grained mill tailings. These mixed deposits overlie fine-grained mill tailings that were discharged into or accumulated in premining ponds. The coarse mine waste probably was transported downstream during flood events after a structural failure at the abandoned Frohner mill. Fine-grained mill tailings with ore-related metal enrichments were redistributed by stream action along Frohner Meadows Creek between the debris fan and the area of line 2. Each of the eight cores analyzed in this area was enriched in ore-related metals relative to local background.

Weathering in the upper part of the debris fan has leached arsenic, cadmium, and zinc from the surface and caused metal enrichment in the underlying nontailings material. This downward migration of metal has substantially increased the thickness of the enriched intervals. The mean-minimum thickness of the enriched intervals (mill tailings and underlying contaminated material) in this area is 52 cm (20 in). The weighted average concentration (WAC) of these metals for enriched intervals are: 3,500 ppm for arsenic; 12 ppm for cadmium; 270 ppm for copper, 3,500 ppm for lead, and 1,200 ppm for zinc. This level of enrichment is relatively high for arsenic and lead compared to other metal-enriched material in the study area; all concentrations exceed the CBPEC for streambed sediment (table 5). Mine waste in the debris fan contributes little clastic material to streambed sediment downstream during low-flow conditions because the creek is not actively eroding the debris fan. Mill tailings deposited in the meadow are effectively stabilized by heavy vegetation and contribute only a small amount of clastic material to the streambed sediment under low-flow conditions.

Deposits of coarse-grained crushed, but unprocessed, ore, probably from the Frohner mill, are mixed downstream with fine-grained mill tailings and fluvial mill tailings from the Frohner and Nellie Grant mines. This material is impounded behind a large reinforced beaver dam. Typically, quartz-rich, fluvial mill tailings mixed with fluvially transported, crushed-ore material overlies thinly bedded fine-grained mill tailings that were deposited in shallow ponds. The calculated mean-minimum thickness of enriched material in this area is 79 cm (31 in.). However, the mean thickness is likely to be somewhat greater, because the bottom of the enriched material was not reached in cores from the mill tailings fan on the west side of Upper Frohner Meadow (fig. 13). The WAC metal concentrations of the enriched material are 2,000 ppm for arsenic, 36 ppm for cadmium, 290 ppm for copper, 2,700 ppm for lead, and 2,900 ppm for zinc. The levels of enrichment are high for cadmium and zinc relative to WAC concentrations from Area A upstream from this area. However, this enriched material far exceeds CBPEC concentrations for streambed sediment (table 5) for all five ore-related metals. Samples from line 4 below the impoundment dam show a moderate thickness of enriched material in one of two sites. The core at site 4-0 is characterized by minor enrichment of arsenic that may be the result of subsurface ground-water transport from the main mill-tailings impoundment and substantial enrichment of cadmium and zinc relative to samples from line 3 that probably result from solution-transported metals in surface water from upstream sources.

The main source of enriched material in lower Frohner Meadows is the mill tailings delta in the water-filled pond at the west end of the meadow (fig. 10). This delta consists of mill tailings from the latest production episode that ended in the early 1980s at the Nellie Grant mine. The results of the one core from the delta (LFMC 1) show that contaminated material in the core is 96 cm (25 in) thick at the southern end of the delta where it is above water. The thickness may increase where it is submerged in the pond. The thickness-weighted mean concentrations of 2,300 ppm for arsenic, 50 ppm for cadmium, 240 ppm for copper, 1,800 ppm for lead, and 5,200 ppm for zinc are about 50 percent of the metal concentrations found in the bulk surface sample from the exposed portion of the delta (LFM 1) (Klein and others, 2003b) suggests that these deposits may be stratified. The extent of the mill tailings is not well documented; the horizontal extent and thickness of contaminated material in the pond were not established.

Downstream from the mill-tailings delta, core samples in lines 5 and 6 have WAC concentrations of enriched material of 280 ppm for arsenic, 11 ppm for cadmium, 190 ppm for copper, 600 ppm for lead, and 850 ppm for zinc. This level of enrichment is relatively low compared to the material upstream in areas A and B, but all concentrations exceed the CBPEC for streambed sediment (table 5). Sampling was not sufficiently extensive to determine a mean thickness, but all of the sampled enriched material is from shallow, buried fine-grained pond-fill deposits or present-day meadow soils. A breached beaver pond at line 6 contains high concentrations of arsenic, cadmium, lead, and zinc in a thin surficial layer of fine-grained, organic-rich pond bottom material that is eroding into the active channel during periods of high water (fig. 14). Streambed sediment downstream plots (figs. 16, 17, 19–21) suggest metal input into the stream from the mill-tailings delta at head of lower meadow.

The wetlands near the outlet of lower Frohner Meadow (above site L-3b and L-158, fig. 3) provide a barrier to clastic-sediment transport and may be accumulating cadmium and zinc from ground and surface water in manganese-oxyhydroxide grain coatings of streambed sediment and buried sediment.

The sediment-filled reservoir in upper Lump Gulch (fig. 3) contains low and erratic enrichments of arsenic, cadmium, lead, and zinc in cores. Low-level arsenic, cadmium, and zinc accumulations are associated with manganese enrichments in cores that suggest these metals are being accumulated by manganese oxyhydroxides from ground and surface water flowing from Frohner Meadows into upper Lump Gulch. Lead, enriched in the deepest part of core ULGFR 3, probably is in clastic material that was deposited early in the sedimentation history of this site and may be a premining natural enrichment. Streambed sediment at the northwest side of this reservoir (site L-158) contains very high concentrations of arsenic, cadmium, lead and zinc, similar in magnitude to those at site L-3b immediately upstream. Cleanup of the present-day channel fill material in the sediment-filled reservoir may eliminate some easily transported metal-enriched clastic material from further transport in upper Lump Gulch, but removal of the deep-fill material underlying the reservoir site might not be necessary or desirable because it may be attenuating some arsenic, cadmium and zinc from ground and surface water flowing from Lower Frohner Meadows into upper Lump Gulch.

An unused reservoir in “Panama mine meadows” (fig. 3) is filled with medium-to coarse-grained granitic debris from the surrounding bedrock. Samples from one core contained localized low-level enrichment of lead and arsenic in the fine-grained pond bottom sediment; the source of the enrichment is not clear. Two possible sources of the enriched material are (1) material transported from several small mines located on the drainage divide above the reservoir about 1 mile west of the reservoir (Becraft and others, 1963); and (2) material derived from unexploited deposits in a poorly exposed-vein system above the reservoir. No significant enrichment of ore-related metals was observed in the streambed sediment downstream from this reservoir.

Chemical analyses of streambed sediment in the study area indicate substantial enrichment in ore-related metals downstream from the mine waste and mill tailings relative to watershed-background concentrations (table 5). These enrichments typically are from 5–250 times higher than the median upper Prickly Pear watershed-background concentrations for arsenic, 3–75 times higher for cadmium, 1.5–10 times higher for copper, 2.5–300 times higher for lead, and 4–75 times higher for zinc in 15 of 18 sample sites in the meadow area. Most of the sites also exceed the CBPEC streambed-sediment, screening concentrations of MacDonald and others (2000) for arsenic, cadmium, lead, and zinc.

The highest concentrations of lead are below the Frohner mill in Frohner Meadow Creek. These concentrations decrease toward the meadow outlet (site L-3b, fig. 3) indicating lead minerals are transported as clastic grains that are diluted by less-enriched material. The main mill-tailings pond (Area B, fig. 3) and Nellie Grant mill-tailings fan in the lower meadow (Area C) are minor sources of lead enrichments downstream from those sites. Material in the main Frohner mill-tailings pond enriches streambed sediment below the pond in arsenic, cadmium, lead, and zinc to a greater degree than that seen in sediment below upper mill tailings (Area A). The highest concentrations of arsenic, cadmium, and zinc in sediment are at meadow outlet (site L-3b). This lack of apparent dilution through the meadow system suggests that these metals were transported in dissolved or suspended form in surface water and enriched by redeposition, perhaps by adsorption on iron and manganese oxyhydroxide grain coatings or in colloidal material near the meadow outlet. Metal concentrations at site L-158, which is immediately below the outlet of Frohner Basin and upstream from the sediment-filled reservoir in Upper Lump Gulch (fig. 3), are highly enriched relative to watershed-background concentrations for all ore-related metals except copper. These concentrations are similar to those at L-3b, located at the outlet to Frohner Basin and immediately upstream from L-158, for all metals except lead, which is markedly higher. These high lead concentrations may be due to the local accumulation of metal-rich clastic material at the break in gradient at the edge of the sediment-filled reservoir during a large flood event. Substantial decreases in all ore-related metal concentration are apparent between L-158 and L-156 immediately downstream from the outlet of the sediment-filled reservoir. These decreases probably are due to dilution from the unnamed tributary that enters the filled reservoir from the south.

Discharge of ground water from unconsolidated deposits plays an important role in maintaining the wetland environment of Frohner Meadows. Ground water, moving from topographically higher areas within Frohner Basin, predominantly flows through thin unconsolidated deposits and the uppermost weathered zone at the top of bedrock and discharges to land surface in wetland areas of Frohner Meadows. Discharge of ground water in the wetland areas also contributes to small increases in stream discharge, especially in the downstream part of upper Frohner Meadows. Discharge of ground water through moraine and bedrock downstream from lower Frohner Meadows is small.

Frohner Basin surface water is drained entirely through Frohner Meadows Creek, which drains into Lump Gulch and eventually into Prickly Pear Creek. Frohner Meadows Creek flows adjacent to the Frohner Mine and enters the wetlands in the northwestern part of upper Frohner Meadows. An unnamed tributary, referred to as “Nellie Grant Creek” in this report, drains from the Nellie Grant mine and enters the wetlands in the west-central part of upper Frohner Meadows. Calculated mean-annual stream discharge of Frohner Meadows Creek at the outlet of lower Frohner Meadows is 0.98 ft^3/s. Calculated mean monthly stream discharge ranges from 0.19 ft^3/s in January to 3.8 ft^3/s in May.

An annual-water budget for Frohner Basin was developed to evaluate relative volumes of water that discharge through surface water, ground water, and evapotranspiration. Average-annual precipitation is about 25 inches and produces about 1,733 acre-ft of recharge on the 1.30 square-mile drainage basin. That volume of water leaves the basin as stream discharge (41 percent of total), evapotranspiration from wetlands (4 percent of total), evapotranspiration from forest and grass (55 percent of total), and groundwater discharge through till and bedrock (less than 1 percent of total).

Dissolved arsenic was present in most (10 of 14) ground-water samples in concentrations exceeding the Montana numeric water-quality standard for human health of 20 µg/L in ground water (Montana Department of Environmental Quality, 2002). The largest concentration (3,380 µg/L) was measured in a sample collected on October 17, 2001, from well FM-1 completed in an area of mill tailings in upper Frohner Meadows (fig. 22). Water from well FM-4, which is completed in an area of fluvial-mill tailings derived from the Frohner Mine, also had a high concentration of arsenic (414 µg/L). Concentrations of dissolved cadmium, copper, and lead were low in samples from all wells completed for this study and were below the human-health standards for drinking water (Montana Department of Environmental Quality, 2002). Dissolved zinc concentrations ranged from less than 1 µg/L in a sample from well FM-3 to 419 µg/L in a sample from well FM-9. High concentrations of cadmium and zinc measured in ground water in well

MW-1, which was completed in a previous study, suggest that these metals may be transported by infiltration of contaminated surface water from Nellie Grant Creek into upper Frohner Meadow at the local scale.

Concentrations of ore-related trace metals in tributaries to Frohner Meadows vary greatly by source of inflow. Small, undisturbed tributaries typically have low concentrations of arsenic, cadmium, copper, lead, and zinc. Frohner Meadows Creek, which drains the area that includes the Frohner mine, has higher concentrations of trace metals than the small tributaries that have no mining disturbance. The highest concentrations of all ore-related trace metals were measured in Nellie Grant Creek, which drains the underground workings and reclaimed area of the Nellie Grant mine.

Instantaneous loads of trace metals into and out of Frohner Meadows were calculated from instantaneous stream-discharge concentrations and measured concentrations of total-recoverable trace metals in water samples. Small tributaries sampled at sites A, B, C, and D (fig. 22) had small loads of trace metals for both the June and August sample sets. The larger tributaries of Frohner Meadows Creek, where they enter upper Frohner Meadows (site F), and Nellie Grant Creek (site G) contributed the largest loads of total-recoverable arsenic, cadmium, copper, lead, and zinc to upper Frohner Meadows. The largest arsenic loads in surface water were measured in Frohner Meadows Creek at sites H, I, and J, which are downstream from Nellie Grant Creek and the main mill-tailings deposits in the central part of upper Frohner Meadows. The large arsenic loads at these sites indicate that additional arsenic is entering Frohner Meadows Creek from mill tailings and ground water in that area. A major part of the cadmium load in Frohner Meadows Creek is contributed by Nellie Grant Creek, which drains the area of the Nellie Grant mine.

CONCLUSIONS

- The mine and mill sites at the Nellie Grant and Frohner mines contribute significant amounts of ore-related metals to streambed sediment and surface water in the study area.
- Most surface-water sites in Frohner Meadows below Nellie Grant Creek exceed the Montana aquatic life standards for the ore-related metals cadmium, copper, lead, and zinc (Montana Department of Environmental Quality, 2002).
- A plume of ground water, rich in ore-related metals that likely are derived from infiltration of contaminated surface water at the outlet of Nellie Grant Creek, locally transports arsenic, cadmium, and zinc into upper Frohner Meadow.
- Arsenic is transported in shallow ground water in concentrations that exceed the Montana numeric water-quality standard for human health throughout much of Frohner Meadows (Montana Department of Environmental Quality, 2002).
- Much of the metal-enriched material in the meadow and wetlands is buried and not identifiable from surface features and has an extent greater than the obvious nonvegetated areas in upper Frohner Meadows.
- Lower Frohner meadow is effective in trapping clastically-transported ore-related metals.
- Mill tailings in upper lower Frohner Meadow have a high acid-producing potential, and if oxidized during weathering, could release high concentrations of arsenic, cadmium, and zinc. Removal of this material should be considered.
- Estimates of premining background concentrations from buried alluvial and pond-fill deposit for Frohner Meadows are 2.4 to 4.6 times higher than watershed background concentrations for active stream sediment in the Prickly Pear watershed for arsenic (4.1x), lead (4.6x), and zinc (2.4x) indicating that Frohner Meadows area contains higher natural premining concentrations of these metals relative to normal regional concentrations in areas of the Prickly Pear Creek watershed with unmineralized bedrock. The premining background concentrations in Frohner Meadows are similar to those of premining sediment in the adjacent upper Boulder River watershed (Church and others, in press) for arsenic, cadmium, and copper whereas they are substantially high for lead and zinc. These high background levels in buried premining material are an important consideration when developing remediation plans.
- Excavation and replacement of contaminated material in upper Frohner Meadows may be a viable option for remediation. However, without a reduction of ore-related metals from upstream sources, such as adit water and mine and mill waste, recontamination of the Frohner Meadows is likely. The wetlands in lower Frohner Meadow appear to be effective in attenuating the concentrations of the clastically-transported ore-related metals in downstream streambed sediments and some water transported ore-related metals by sorption under current conditions. Disturbance of these wetlands could result in a change in surface- and ground-water chemistry and hydrology that may result in high-metal load of arsenic, cadmium, and zinc in surface water downstream in upper Lump Gulch and also alter the ability of the wetland to trap clastic-sediment particles.

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